MARCH 1950

Chemical Engineering Progress

PUBLISHED MONTHLY BY THE AMERICAN INSTITUTE OF CHEMICAL ENGINEERS

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Chemical Engineering Progress

MARCH 1950 — Volume 46 • Number 3

PUBLISHED MONTHLY BY AMERICAN INSTITUTE OF CHEMICAL ENGINEERS

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"ΟΦΡΑ ΘΕΕΙΩΣΩ ΜΕΓΑΡΟΝ
Odyssey, xxii, 481

"QUICKLY, O! DAME, BRING FIRE THAT I MAY BURN SULPHUR, THE CURE OF ILLS." So spoke the warrior, Ulysses, after forcefully ridding his home of Penelope's suitors on his return from the siege of Troy. Homer called burning Sulphur, "Divine, Purifying Fumigation". Indeed, Sulphur so impressed the ancients that they used it even in their religious rites.

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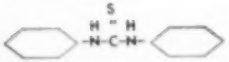
Research Chemists' Corner

You may find something new here

Chemists who are looking for ways to improve their products or develop new ones may profit from studying the specifications of Monsanto's thiocarbanilide (diphenyl thiourea) given here. Research in the application of this product is far from exhausted. It may hold the secret of great forward steps for your business. If you'd like to test thiocarbanilide for its possibilities in your projects, we'll be pleased to send you a sample without cost and without obligating you in any way. Just indicate your wishes on the coupon!

THIOCARBANILIDE
(Diphenyl Thiourea)

Structure:



Moisture:	0.5% maximum (test must avoid decomposing conditions)
Ash:	0.5% maximum
Specific Gravity:	1.32 @ 25° C.
Solubility:	Soluble in alcohol. Insoluble in water and many other common solvents.

Two grades are available, one a white powder melting at 148° C. minimum and the other a white-to-grey powder melting at 146° C. minimum.

Reactions: A weak organic base. Boiling with hydrochloric acid results in formation of phenyl isothiocyanate. The sulfur can be removed by PbO in alcohol solution forming carbodiphenylimide or, in the presence of ammonia, diphenylguanidine. Condensation with CS_2 and sulfur under pressure produces 2-mercaptobenzothiazole.

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Whether you use phenol for any of various products, ranging from pharmaceuticals to photographic chemicals, you can get the form you want from Monsanto. Monsanto Phenol is available as: Phenol, U.S.P.; liquid phenol, 85% solution; and liquid phenol, 88% solution. Delivery of phenol, or any of the long list of Monsanto Intermediates, can be made promptly from the Monsanto Warehouse nearest your plant.

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ortho-Chloroaniline
para-Chloroaniline
ortho-Chlorophenol
para-Chlorophenol
Cyclohexylamine
Dicyclohexylamine
Dinitroaniline
Dinitrochlorobenzene, 46.5°
Dinitrochlorobenzene, 48.0°
Monsanto Salt
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ortho-Nitrobiphenyl
para-Nitrobiphenyl
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TRI SODIUM — Water softeners, detergents, metal cleaners, textiles.

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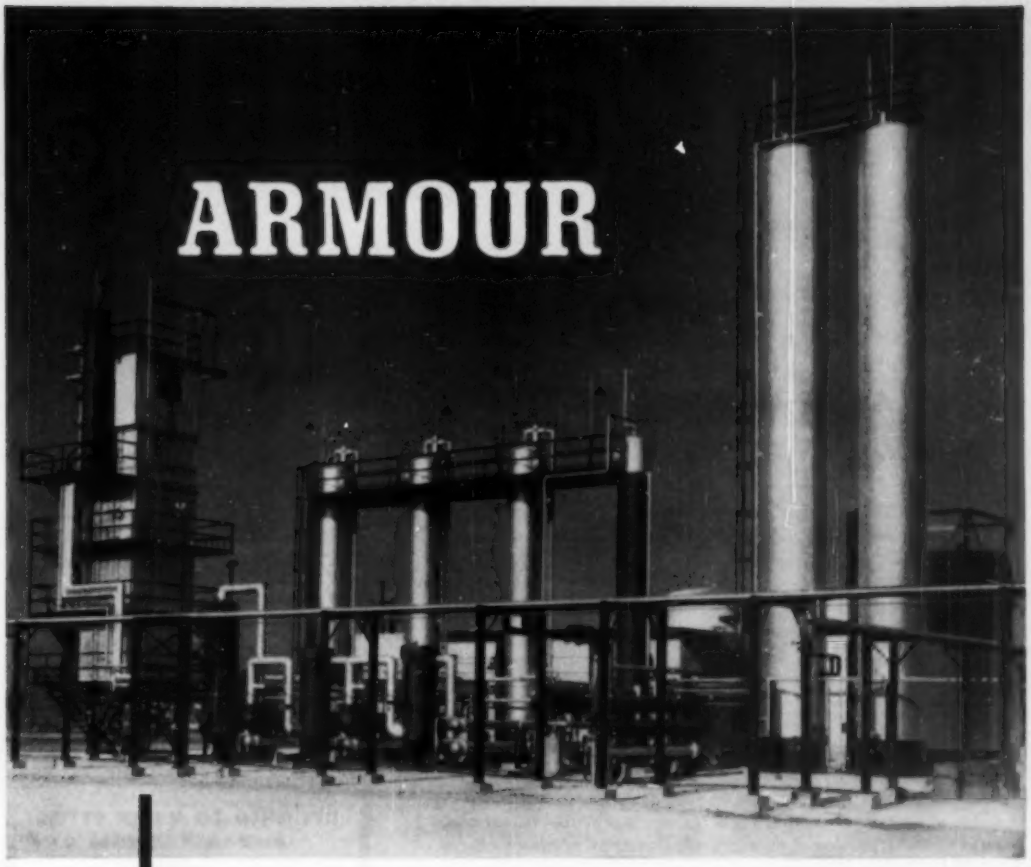

Armour gets lower costs

with a **Girdler Hydrogen Plant**

AS A RESULT of years of research and development, Armour and Company has recently expanded its operations in the chemical field. An important part of this program called for a dependable, continuous supply of low cost hydrogen. That need has been met to a high degree of satisfaction by the modern Girdler *Hygirtol** Plant shown above, located at McCook, Illinois.

The hydrogen plant at McCook is the third Girdler *Hygirtol** Plant purchased by Armour and Company. All of these plants were designed and built by Girdler engineers.

Let Girdler serve *you* in your problems involving gas processes. Girdler designs and builds facilities to produce, purify or use chemical process gases, liquid and gaseous hydrocarbons, and organic compounds . . . Write for further information.

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Better Flow—straight-through ports are non-restricting to flow; minimize turbulence and corrosive action.

Tight Seating—18-8 Mo renewable screwed-in shoulder-type body seat rings do not loosen in service. Full length integral disc guides keep disc travel true; eliminate drag and undue wear on seating surfaces.

No Stem Binding—Two-piece ball-type gland maintains uniform pressure on packing; prevents binding on stem when gland bolts are not pulled up evenly.

No Side Strain On Stem—"T-head" disc-stem connection prevents any side strain on stem; gives flexibility for smooth operation.

Send for Circular No. 320

For further information about these—and other—corrosion-resistant valves, see your new No. 49 Crane Catalog, or send for Corrosion-Resistant Piping Materials Circular No. 320. No obligation.

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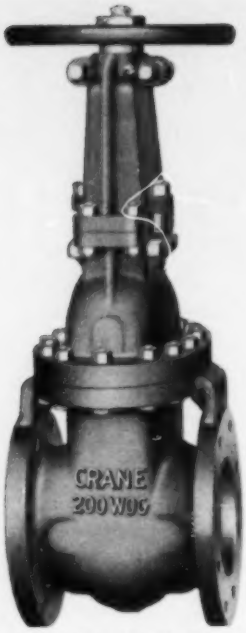
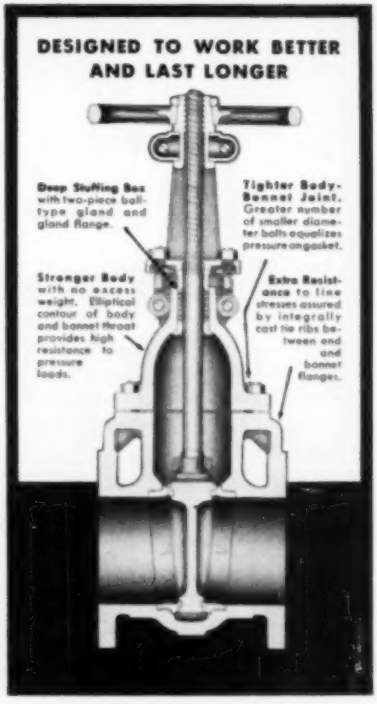


No. 14447 Gate 18-8 Mo Trimmed. Working Pressure: 200 pounds cold water, oil, gasoline or gas. Sizes: 2 to 12 inch.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Deep Stuffing Box with two-piece ball-type gland and gland flange.
Tighter Body-Bonnet Joint. Greater number of smaller diameter bolts equalizes pressure on gasket.
Stronger Body with no excess weight. Elliptical contour of body and bonnet throat provides high resistance to pressure loads.
Extra Resistance to line stresses assured by integrally cast tie ribs between end and bonnet flanges.

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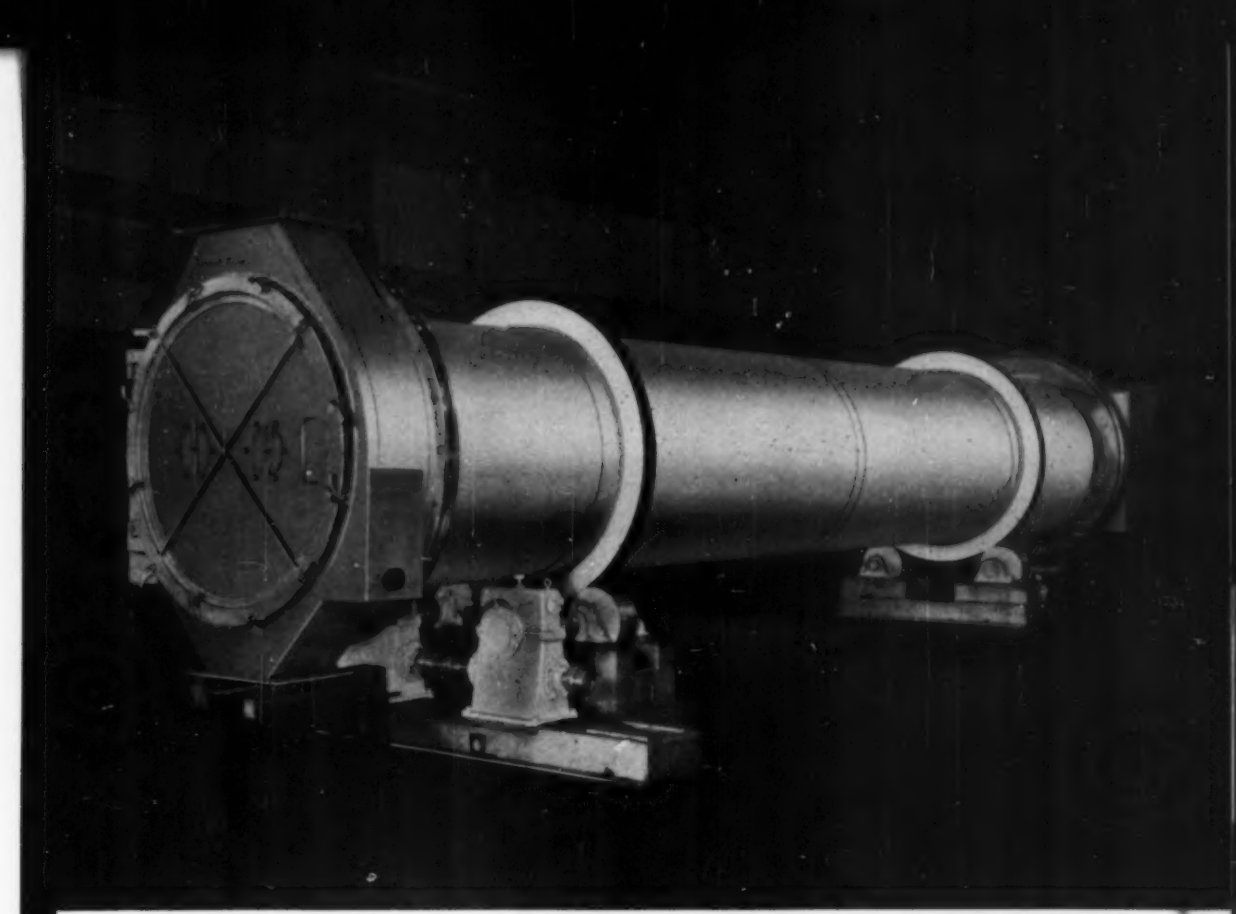

It keeps the RED from the WHITE and the BLUE

FABRICATED entirely of stainless steel, the 60" diameter by 32'0" dryer pictured above is probably one of the most costly direct heat rotary dryers (of its size and weight) ever built.

The entire interior, including the flights, is polished to a mirror like satin finish, and is easily accessible for thorough cleaning. Both the feed and discharge breechings, complete with their air-tight inspection doors and labyrinth seals, are also stainless steel, polished to a satin finish on the inside.

To assure a satisfactory product free from contamination, the air used in drying is first filtered through an air filter. This air on leaving the dryer goes to a cyclone dust collector of Bartlett-Snow's special high efficiency design. This equipment also is of stainless steel construction, and polished, and all parts of the equipment are enameled on the outside as a further aid in preventing contamination.

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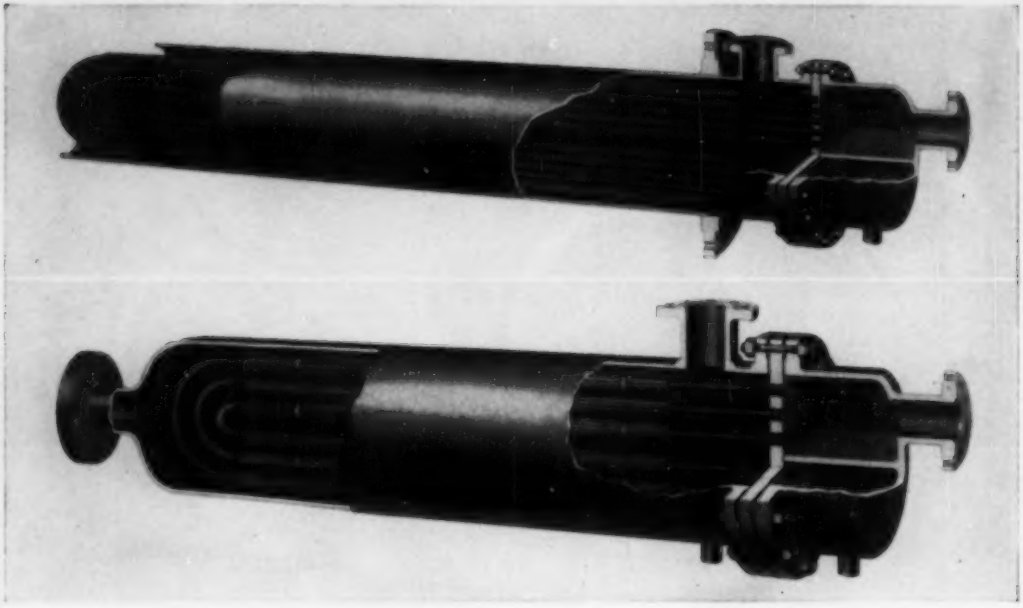


BROWN FINTUBE

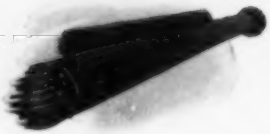
Tank Suction Heaters and Line Heaters

● Brown Fintube Tank Suction Heaters are moderately priced and highly efficient. They heat viscous oils so that they can be pumped more easily, and bolt or weld to a tank nozzle, or directly to the tank shell, so all piping and connections are made outside the tank.

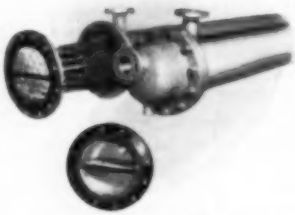
The Line Heaters are used as Suction Heaters to permit easier pumping of viscous oils; – or as Pressure Heaters, either to overcome temperature losses in long lines, or to preheat liquids for further processing.

In all cases the bundles consist of Brown Fintube hairpins rolled into the tube sheet in full compliance with the ASME codes. Metal bands, placed around alternate fintubes, prevent the longitudinal fins from interlocking and restricting the flow. This construction avoids baffling, and permits the liquids being heated to pass through the bundle *unobstructed*, in close contact with the fins and center tubes, with *low pressure drop*. Wide range of standard sizes.

Send for Bulletin No. 482. It gives full details.
Let us quote on your requirements.



Brown Fintube Hairpin Bundles Showing the Banding of Alternate Tubes that Eliminates Baffles and Assures Unobstructed Flow.



Hairpin Bundle Assembled in Shell Showing Mounting of Tube Sheet Between the Shell and Head.

THE BROWN FINTUBE CO.
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FINTUBE HEAT TRANSFER PRODUCTS

look to DOW for

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SPECIFICATIONS:

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WITH PFAUDLER'S STANDARD LINE OF STAINLESS STEEL EQUIPMENT

Q. *Of what does Pfaudler's standard line of Stainless Steel process equipment consist?*

A. A series of engineered stainless steel jacketed reaction vessels with motor driven agitators ranging in size from 5 to 500 gallons; jacketed evaporating pans in 12, 60 and 150 gallons; heat exchangers and condensers in various designs and capacities.

Q. *What has guided you in designing this equipment to assure good performance?*

A. Over 20 years of engineering experience in designing all types of stainless steel chemical process equipment. The most efficient designs were selected from this experience from the standpoint of size, design, agitation, heat transfer and cost. Pfaudler pioneered in perfecting the technique of stainless steel welding.

Q. *How do you handle various requirements from standpoint of corrosion resistance?*

A. Stock units are made of type 316 but ample inventories are carried of types 304, 321 and 347 for quick delivery. Pfaudler also has facilities for heat treating and passivating where required.

Q. *How can I get the complete story?*

A. Ask for Bulletins 823 and 837 or call the nearest Pfaudler sales engineer.

When standard designs won't answer your needs, Pfaudler engineers stainless steel to your requirements.

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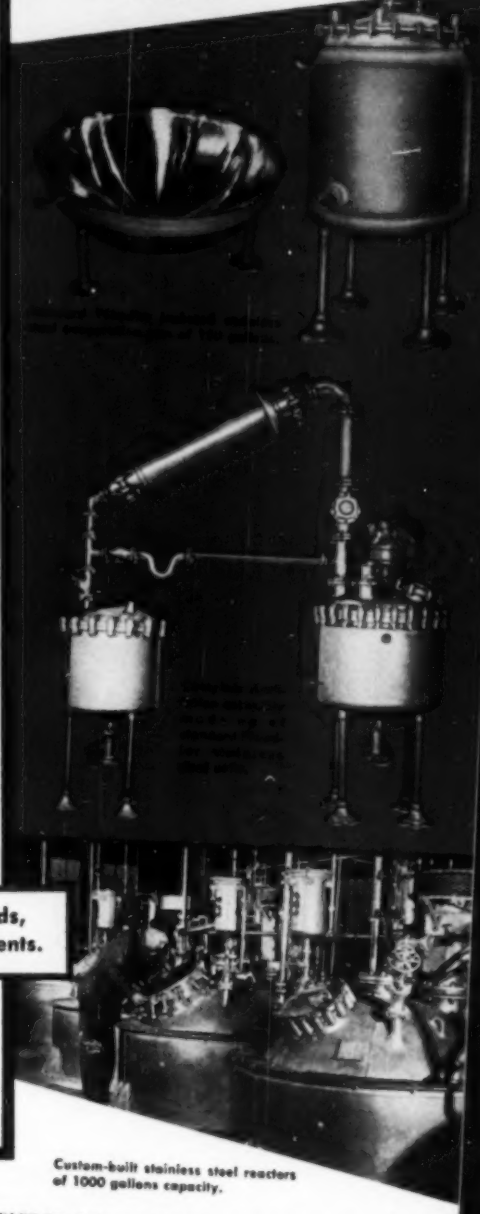

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OPINION AND COMMENT

EXECUTIVE TRAINING AND DEVELOPMENT

THE training and development of young men so that they can be better prepared to take on more responsibility is one of the most important elements in the business world today. Growth in pension and retirement plans has been a decided stimulant. More and more companies now have compulsory retirement, usually at the age of 65. This means that each year, the older and generally more experienced executives are passing out from the top, thus making room for younger men and their promotion to positions of greater responsibility.

The development of a strong second team which is trained to take over top responsibility five, ten and fifteen years hence is a major concern in all wide-awake, and up-and-coming companies. As a matter of fact, there never seems to be an oversupply of young or middle-aged men who have clearly proved that they are capable of taking on top responsibility.

More articles are being written about the subject of executive training and development than almost any other management activity, except possibly product application and development which also are of great importance.

What are some ways in which a company can go about the selection, training and development of the young men who will be taking over positions of top responsibility fifteen or twenty years hence? The first step must obviously be appraisal and selection of new employees. The calibre of the men who will be running the company in the distant future depends to a considerable extent on the selection in the employment office of young men of latent ability now. Space does not permit further elaboration of this job of skillful selection so that men of real promise can be taken on and infused into the bloodstream of an organization, but it is the first important step.

The next step is to put these new men to work. At first, it does not matter too much where they are put to work, although this should not be taken too literally. The point is that, after working six months or a year at something, the young man who has initiative, imagination and the knack of getting along well with his fellow-workers will begin to show up. Special aptitudes begin to be evident which, in those companies which are really trying to do a job of developing their younger men, will lead to special assignments where the young man's indicated abilities can prove most useful. Many times things do not work out exactly this way, but the trend is in this direction.

At this stage, a rating of the employee by his closest supervisor is likely to be helpful and is made from time to time in many companies. Again, much has been written about merit ratings. Obviously certain characteristics should weigh more heavily than others. Initiative, imagination and cooperation with others have already been mentioned, and should assuredly be near the top. Willingness to work hard, common sense and judgment must also take an important place. It is assumed that the man's technical ability is adequate, and this of course cannot be ignored. It is important that, when the man has been rated, his rating be discussed with him by his immediate supervisor. If the latter does a good job in talking over the rating with the candidate, great benefits can accrue and a subsequent rating will show real improvement if the candidate is the right kind of person for the job.

When it is becoming obvious which young men are beginning to stick their heads up above the pack, the next step in the training program can well be a series of carefully planned assignments extending over a period of years, which assignments are directed toward giving the man experience in different departments or phases of the business. Management is sometimes loath to afford this kind of broad experience to their younger men because it may involve added labor expense. No belief could be more shortsighted. If the candidates have been carefully selected, they will be good enough men so that they will pay their way no matter what they are assigned. Even if this were not the case, what better investment can be made than the training of those men who are to comprise the management team of the future?

Participation, by invitation, in executive conferences where important decisions are reached or important policies are developed is a most helpful method of training, as are group meetings at which a company executive talks about various phases of the business.

During the training years, the importance of human relationships should be stressed. The candidate should be taught to be a leader, not a driver; he must be fair; he must be honest with himself and others; and he should give credit where credit is due, unless it is to himself.

What is the end result? An important vacancy occurs either because of illness, resignation, retirement, transfer, or promotion, and instead of being forced to reach an emergency decision, the company which has been maintaining for years an adequate system of personnel selection and development will have little or no difficulty in picking the right man almost immediately to fill the created vacancy.

When a man has been selected and is promoted to a top job, he should be given plenty of rope and put very much on his own. If he has been properly trained, he will not need much supervision.

A really good executive invariably spends much of his time in training one or more men to take his place. Although this may seem difficult at times, it is a must. Organization charts which show the retirement date and age of each supervisor have proved a good stimulant to developing men to fill the vacancies which lie ahead.

A little pamphlet entitled "Bottom-Up Management" by William B. Given, Jr., president of the American Brake Shoe Co., is one of the most inspiring articles recently written and has real bearing on the subject discussed here.

It is too easy to put off until tomorrow the development of men who are to carry the load in the future. Prepare in advance for emergencies, don't wait for them. Remember, "it's later than you think!"

R. L. Murray

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Chemical engineers must consider other things in building a plant beside the equipment size and capacity according to these authors. . . . Return on investment and maximum profit for invested money will often make a difference in the equipment selected, size of pipe and, whether new boilers are bought or the old boilers rehabilitated. . . . Taxes are an important item. . . .

VENTURE PROFITABILITY IN ECONOMIC BALANCES

JOHN HAPPEL * and R. S. ARIES †

A method for judging the attractiveness of new projects and for designing process plants has been developed in which proposed new ventures are compared on the basis of maximum additional profit above a predetermined rate of return consistent with the risk involved. Applied to the design of the component parts of a plant, the index specifies that the last increment of investment shall yield a satisfactory return. Whether this return rate is determined by the engineer or management, it is shown that such a figure must be available to the designer if he is to arrive at a selection of sizes and conditions which will constitute an optimum. Equations and examples illustrate the method.

THE term "economic balance" in chemical engineering problems generally refers to calculations made to determine the conditions for realizing maximum return from manufacturing operations. General considerations which form the framework upon which sound decisions must be made are simple. Sometimes their application to the problems encountered in the development of a commercial enterprise involves too many intangibles to admit of exact analysis, in which case judgment must be intuitive. Often, however, calculations may be made covering various phases of chemical processes with a considerable degree of exactness. It is believed that the usefulness of such calculations could be extended by an exact formulation of their application to business decisions. The purpose of the following discussion is to develop some relationships in this field.

Project Analysis

Evaluation of the attractiveness of a new proposition usually involves the preparation of simplified forms of income account for a number of alternatives similar to those used in reporting profits. Such statements can be compared then with actual statements of going ventures in the same field and with other propositions. The net profit of a venture may conveniently be expressed in terms of gross earnings, investment, taxes and depreciation.

For the present discussion, the relationship of profit to these other variables may be expressed by a simple formula, involving the following assumptions: Depreciation is taken at 10% per year on the investment and it is assumed that this rate will also be allowed by government authorities for tax purposes. The duration or life of the project in question is also assumed to be 10 years with negligible salvage value. It is also assumed that interest on capital investment may be neglected (though in the equations this can readily be taken into account). The equivalent return, as used here, is based on capital invested in equipment, not investment plus working capital, and is considered as being received annually over the entire period from the start of construction until the venture is closed out. Tax rate is taken at 38%, the Federal corporation income rate applying to incomes more than $50,000 per year. With these assumptions the net profit P may be calculated. The taxable income will be $(R - 0.1\,I)$. The tax is then $0.38\,(R - 0.1\,I)$. Thus,

$$P = R - 0.1\,I - 0.38\,(R - 0.1\,I)$$

$$P = 0.62\,R - 0.062\,I \qquad (1)$$

and the annual rate of return on investment expressed as a per cent is as follows:

$$p = \frac{P}{I} \times 100 \qquad (2)$$

where

I = capital investment in a venture, $

R = gross yearly earnings from a venture before deducting income tax and depreciation, $ (= sales realization less raw materials costs, operating costs, maintenance costs, insurance, social security and unemployment taxes, etc., but before deducting income tax and depreciation)

The important distinction to be drawn between a projected income statement derived from an engineering study and one from an actual business is the fact that in the former case a greater risk is involved. To be comparable, therefore, the return indicated in Equation (1) for a proposed venture must be modified to allow for the possibility of failure and the effect of this eventuality on the company or individual investing the capital. A going concern will have its funds all invested in a number of ways at returns commensurate with the risks involved, and when a new proposition involving a *given risk* is considered, the currently obtained base return will be the prerequisite for further consideration. Maximum profit

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to the concern will result to the extent that money invested at *this risk* can yield a higher return. If more than one new proposition is involved, the one returning the maximum additional money above the base return for each will be the one selected.

The minimum acceptable base return may be designated as P_A and the corresponding rate as p_A. The additional profit, which is the motivating force attracting venture capital to new enterprises may be designated as "venture profit" to distinguish it from profit normally expected in the usual conduct of business. Venture profit, V, will then be expressed as follows:

$$V = P - P_A = 0.62R - 0.062I - \frac{p_A I}{100} \qquad (3)$$

In evaluation of new projects, the one showing the highest venture profit will be the most attractive.

Note that the use of this method is equivalent to comparing the rate of return on incremental investments for a series of proposals involving different investments, but the same risk. The last increment of capital which should be invested will return at a rate equivalent to p_A and will correspond to the point of maximum venture profit. If a number of alternates is involved, the direct calculation of venture profit is more convenient. If the propositions involve different risks so that p_A is different for each proposal, the incremental method cannot be readily used, but the venture profit method is still applicable.

Other Methods

It is believed that the venture profit method constitutes means for establishing choices between alternatives which is free from the disadvantages of some of the methods in current use. Some of these techniques will be considered and compared with the venture profit method to show why this is so.

One procedure often used involves in effect, a direct comparison between rates of return on investment, thus employing Equation (*2*) directly rather than comparing the amounts of return above a specified acceptable minimum rate. A simple modification of this method which is also commonly used is the use of the index "payout time." Payout time is simply the time required for gross yearly earnings to equal the investment:

$$T = \frac{I}{R} \qquad (4)$$

where T = payout time, years.

This formula is easy to use since it avoids estimating such items as depreciation, life of plant and taxes. It is obvious that Equations (*2*) and (*4*) are directly related to each other. Thus a return, p, of 30% is equivalent to a payout time, T, of 1.7 years

$$\left(\text{or in general} \quad T = \left(\frac{0.62}{\frac{p}{100} + 0.062} \right) \right)$$

using the assumptions made in deriving Equation (*2*).

The objection to using Equations (*2*) or (*4*) directly in comparing projects is that, other changes being equal, they do not show that a large investment at an attractive rate of return is more desirable than a smaller one at the same rate. One way to show this is the "cash position" method. This involves tabulation of the net increase in total assets resulting from a given number of years of operation. Thus the profits remaining after income tax is deducted are first used to retire the original investment and thereafter accumulate as a cash reserve. (It is assumed that no interest accumulates on such a reserve.) In this case the base for return is the same as in Equation (*2*) except that depreciation (0.1 I) is not deducted from the gross profit because cash position directly allows for retirement of investment. Thus, letting y equal the number of years' operation, the cash position C at any time will be:

$$C = (0.62R + 0.038I)y - I \qquad (5)$$

The above formula will, of course, apply only during the 10-year period when the investment is being depreciated; thereafter the 0.038 I should be omitted.

The cash position method has this disadvantage: a large investment, even at a low rate of return, will show a substantial increase in total assets over a period of time.

Use of the venture profitability method combines the desirable features of both the rate of return (or payout) method and the cash position method. It gives due weight to the fact that a high rate of return is desirable but that the larger the investment based on which it is taken, the more attractive a proposition will be. It requires use of one additional item of information, namely the minimum percentage return necessary for the risk involved p_A (or alternatively T_A).

Determination of Risk

Determination of the risk involved in a given enterprise is largely a matter of judgment based on past experience. An approximate guide along these lines is given in the following table based on a recent survey (*1*).

TABLE 1.—MINIMUM ACCEPTABLE NET PROFIT* ON INVESTMENT IN THE CHEMICAL PROCESS INDUSTRIES AS RELATED TO DEGREE OF RISK UNDER TAKEN†

	Average Minimum Acceptable Net Profit, p_A Per Cent, for	
	Low Risk	High Risk
Industrial chemical	7	27
Petroleum	10	24
Pulp and paper	11	25
Drugs and pharmaceuticals	15	35
Metals and metallurgy	5	15
Paints, varnishes and lacquers	13	27
Fermentation products	6	30

* In accordance with standard accounting practice net profit is used as defined in the nomenclature.

† General business conditions and the availability of working capital in an industry are important factors in arriving at this minimum acceptable net profit figure.

Table 1 indicates a range of acceptable return rates for several process industries, based on the same assumptions used in developing Equation (*2*). The higher values for acceptable rate of return (corresponding to lower values for acceptable payout time) will apply in the case of new, untried ventures, where extrapolation to plant scale is large and where the market is uncertain. Conversely, the lower values for acceptable rate of return will apply in the case of established business propositions, already on a commercial scale.

These figures, which include allowance for the present high tax rates, compare favorably with those suggested by Redman (*5*), 20 years ago, namely 5% per year on a conservative investment, 12½% per year for competitive industry, and 33½% per year in noncompetitive ventures of the type which result from scientific research. The conclusion is that risks are much the same now as then, and that to attract venture capital today the same net remuneration after taxes must be possible.

If it is desired to use the simpler payout time T_A instead of p_A, it is important to realize that in recent years the changing tax picture has caused a downward revision of the acceptable payout time. Values for acceptable payout times can be computed from values of P_A listed in Table 1. The appropriate formula for venture profit involving T_A instead of p_A is as follows:

$$V = 0.62\left(R - \frac{I}{T_A}\right) \qquad (6)$$

Inspection of Equations (*3*) and (*6*) show that venture profit could equally well be defined without the tax item, provided the same basis is used for both the minimum acceptable and proposed new investments. Tax is included in this discussion to emphasize its present importance.

Plant Design

In making a detailed design of the various component parts of plants, the engineer often has a choice of alternatives for specified duties. Sometimes these alternatives involve a wide and practically continuous range of possibilities and the optimum conditions can be arrived at most readily by a mathematical approach. The same general principles apply as previously described, namely that the venture profit should be a maximum.

Thus, venture profit may be expressed as follows:

$$V = f(a,b,c, \ldots n) \qquad (7)$$

where a, b, c, . . . n are all the variables which enter into the determination of profit. Then partial differentiation of venture profit with respect to each of the variables involved, and setting of the partial derivatives equal to zero will result in n simultaneous equations.

$$\frac{\partial V}{\partial a} = 0; \quad \frac{\partial V}{\partial b} = 0; \quad \frac{\partial V}{\partial c} = 0 \ldots$$

$$\frac{\partial V}{\partial n} = 0$$

Solving these equations will give values of the n variables which maximize profit (*6*). This method may be applied graphically or analytically.

In practical applications, the analytical or algebraic formulation is most often used in cases where profit or some variable related to profit can be expressed under given conditions in terms of one variable. Thus, considering Equation (*3*) and letting $p_A = 30\%$, suppose that gross earnings may be conveniently expressed as a function of investment alone. Then by differentiation of V with respect to I the following results:

$$\frac{dV}{dI} = 0.62\frac{dR}{dI} - 0.362 \qquad (8)$$

and setting dV/dI equal to zero, $dR/dI = 0.584$. That is, the increased gross earnings realized per dollar increase in investment must be equal to $0.584. If it were more convenient to use one of the operating variables as the independent variable instead of I,

$$\frac{dV}{da} = 0.62\frac{dR}{da} - 0.362\frac{dI}{da} \qquad (9)$$

and in this case, $dR/da = 0.584(dI/da)$ represents the optimum condition.

Often the gross earnings will include charges which are directly proportional to the investment, such as maintenance and insurance. In this case, it may be more convenient to break gross earnings, R, down into operating earnings 0, and the fixed charges proportional to investment iI (but not including depreciation which is already included in Equation (*3*)). If this is done Equation (*9*) becomes:

$$\frac{dV}{da} = 0.62\left(\frac{dO}{da} - i\frac{dI}{da}\right) - 0.362\frac{dI}{da} \qquad (10)$$

and for the optimum condition, $dO/da = (i + 0.584)dI/da$.

Equation (*10*) is simply a typical example of the type equation employed and different similar forms could be used in practice. Thus, allowable depreciation rates for tax and bookkeeping purposes might both be different from the 10% employed and the appropriate return on investment might not be 30%. Also, both the operating profit, 0, and the investment, I, might consist of a number of independent terms and there might be more than one independent operating variable, a, employed. In some cases optimum conditions would not involve any change in investment, thus resulting in considerable simplification (*3*). Again a fixed sales price may be assumed for the product or products made and then the minimum cost operation will result in the maximum venture profit (assuming also no investment change is involved). The formulas might also be expanded to take into consideration interest on investment and method of disposing of the profit (using compound interest rates if desirable.) None of these variations, however, alters the basic considerations outlined.

Examples of Application

The following example illustrates how the above formulas may be applied to a choice from among several alternatives:

Example 1. Management has decided to increase production and has asked its engineering department to survey the possible alternatives. The following information has been developed. There are three choices (a) additional facilities to the present equipment at an investment of $200,000 which would return a gross profit of $214,000 per year; (b) a new process which involves, to some extent, use of existing facilities at a new investment of $600,000 which would return a gross profit of $543,000 per year; (c) complete new facilities at a cost of $1,000,000 which would return a gross profit of $745,000 per year on this investment. The risk and capital availability is such that the management feels that a 30% return on capital p_A, after taxes and depreciation is a fair return. Which alternative should be selected?

The following table gives the results of calculations using the above formulas:

TABLE 2.—OVER-ALL PROJECT SELECTION

Alternatives	*I*	*II*	*III*
Investment, (I)	200,000	600,000	1,000,000
Gross earnings, (R)	214,000	543,000	745,000
Net profit, (P)	120,000	300,000	400,000
Payout time, yr.(T)(Eq. 4)	0.93	1.10	1.32
Return, % (p) (Eq. 2)	60	50	40
Cash position after 10 years, (c) (Eq. 5)	1,200,000	2,900,000	4,000,000
Venture profit, (V)	60,000	120,000	100,000
Incremental investment, (ΔI)	.....	400,000	400,000
Incremental profit, (ΔP)	.....	179,000	100,000
Incremental profit rate, % (Eq. 2)	.....	45	25

Thus, while alternate *I* shows the lowest payout time and highest return on the investment and alternate *III* shows the best cash position, it is apparent that alternate *II* will be the best choice because it shows the largest venture profit. Note that if return on incremental investment is employed, alternative *II* will also be selected.

The following examples will illustrate the method as applied to plant design and indicate the differences in procedure from those sometimes employed in making calculations of this type.

Example 2. A boiler house consists of 5 coal-fired boilers, each with a nominal rating of 300 boiler horsepower. If economically justified, each boiler can be operated at a rating of 350% of the nominal. Due to the growth of manufacturing facilities, it is necessary to install additional boilers. From the data below, determine the per cent of nominal rating at which the boilers should be operated.

Data—Cost of fuel, including cost of handling and removing cinders, is $7/ton, and the coal has a heating value of 14,000 B.t.u./lb. The over-all efficiency of the boilers, from coal to steam, has been determined from tests of the present boilers operated at various ratings:

N, % of Nominal Rating	E, % Over-all Thermal Efficiency
100	75
150	76
200	74
225	72
250	69
275	65
300	61

Annual fixed charges y_A on each boiler are given by the equation

$$y_A = 14{,}000 + 0.04N^3$$

Assume 8,550 hr. of operation per year.

The above example is exactly given by McAdams (*7*). To apply the methods presented here the following additional data are required. The equivalent capital for installation of new boiler capacity will be approximately $6/(lb.)(hr.) of steam generated. All direct operating costs for steam generation with new facilities will be about $0.30/M lb. of steam. Since steam is required for a number of operations in a

typical process plant, there is less risk involved in investments in boilers. However, there must be some incentive in addition to the bare depreciation charges (assumed here at 10%) to justify spending money on additional boiler capacity. Assume that a 10% profit will be the minimum satisfactory.

Solution. First compute the marginal value of steam at which new investment will be attractive, that is the value at which the venture profit will be zero:

$$V = 0.62R - 0.062I - 0.1I = 0$$

and therefore,

$$R = 0.26I$$

$$\frac{(0.26I)(6)(1000)}{8550} = 0.184\ \$/M\text{ lb. steam,}$$

gross earnings. Therefore,

$$0.30 + 0.18 = 0.48\ \$/M\text{ lb. marginal value}$$

Secondly, compare this figure with the cost of generation in the old equipment. Assume I boiler hp. = 34.5 lb./hr. of steam (= 33,500 B.t.u./hr.). Optimum operation will result when the out-of-pocket cost for fuel to produce incremental steam equals $0.48/M lb.

C_F = hourly cost of fuel at $7/ton:

$$C_F = \frac{(5)(300)(N/100)(33,500)(7)}{(E/100)(14,000)(2,000)}$$

$$= 12.56\,\frac{N}{E}$$

C_A = hourly fixed charges

$$C_A = \frac{5(14,000 + 0.04N^2)}{8550}$$

$$= 8.18 + 0.0000234N^2$$

Table 3 evaluates the incremental and average costs of producing steam.

Example 3. It is desired to develop an equation for selection of pipe on an economical basis so that the total annual cost of the fluid-handling system for a given duty will be a minimum. To illustrate the method, using the data below, calculate also the optimum pipe diameter for conveying water at 20° C. at the rate of 75,000 lb./hr.

Data.—This problem has been considered by Genereaux (*2*) who gives an over-all equation for the optimum as follows:

$$D_i = \frac{m^{0.445} Z^{0.035}}{\rho^{0.035}} \left(\frac{0.0232YK}{(a+b)(F+1)XE} \right)^{0.356}$$

where D_i is the optimum diameter, in.; m is the weight rate of flow, thousands of pounds per hour; Z is viscosity, centipoises; ρ is density, pound per cubic foot; Y is hours of operation per year; K is cost of electrical energy, dollars per kilowatt hour; a is amortization, fractional (i.e., 0.10 for 10%); b is maintenance, fractional; F is a factor for fittings and erection; X is the cost of one-inch pipe per foot of length, $; and E is the over-all efficiency of pump and motor, fractional.

Genereaux arrived at this expression by differentiation of a relationship expressing total cost in terms of pipe diameter, with respect to pipe diameter and setting the derivative equal to zero. He simplified the general expression still further by using an average of 2.2 for the "fixed cost" portion of the expression and assuming that $Z^{0.035}$ could be taken as unity for all practical purposes. This results in the following expression:

$$D_i = 2.2m^{0.445}/\rho^{0.035}$$

To apply this equation to the method outlined in this paper, it will be assumed that this piping is part of a process plant in which investment of money is not justified unless a 30% return on investment can be realized after taxes and depreciation.

Solution. In addition to the item b in the above equation, representing maintenance, an item for profit of 0.584 will be added in accordance with Equation (10). Thus if Genereaux's assumption is taken that items a and b are 0.10 and 0.06 respectively, $0.584 + 1 = 0.644$ will be used instead of 0.16 for the term $(a + b)$. Consequently, the simplified equation will be:

$$D_i = 1.77m^{0.445}/\rho^{0.035}$$

and for a 75,000 lb./hr. rate of water:

$$D_i = \frac{(1.77)(6.92)}{(3.68)} = 3.3\text{ in.}$$

This compares with Genereaux's figure of 4.1 in. obtained when the problem is solved on the assumption that the piping should be sized to operate at minimum cost rather than an appropriate profit.

Example 4. In many chemical processes heat is used in large quantities and since only a small portion is actually used in the reactions involved, much of this heat may be recovered by means of heat exchangers. The following example illustrates application of the equations developed above to this type of problem.

It is desired to determine the optimum temperature approach between flue gases from a furnace and a waste heat boiler recovering heat from these gases.

Data.—It will be assumed that sufficient draft is available so that no additional blower or stack is required, that the equipment will operate 8400 hr./calendar year and that steam will be generated at 100 lb. gage pressure.

Incremental waste heat boiler surface is worth $3.00/sq.ft. installed and an over-all coefficient of 5 B.t.u./(hr.)(sq.ft.)(° F.) is obtainable. The estimated value of steam is $0.48/M lb. For 100 lb. steam with 90° F. feed, the B.t.u./lb. of steam generated will equal 1,133.

The management is not interested in investing money in equipment of this type at more than a three-year payout. In addition, maintenance and other fixed charges will amount to 6% on the investment.

Solution. If square feet of waste heat boiler surface is designated as the variable, a, an equation analogous to Equation (10) may be obtained as follows from Equation (6),

$$\frac{dV}{da} = 0.62\left(\frac{dO}{da} - i\frac{dI}{da} - \frac{1}{T_A}\frac{dI}{da}\right)$$

and for the optimum condition, using an hourly basis,

$$dO/da = d\left[\frac{(i + 1/3)}{8400}\,I\right]/da$$

since

$$T_A = 3$$

In other words, the savings made on the last square foot of waste heat boiler surface installed must equal total charges at a rate of $(0.06 + 0.333)/8400 = 4.68 \times 10^{-5}$/hr. on the cost of the last square foot.

Since heat transferred per hour per square foot,

$$q/\theta = 5 \times 1 \times \Delta t,$$

the savings on the last square foot will be:

$$5 \times 1 \times \frac{0.48 \times \Delta t}{1000 \times 11.38}$$

$$= 2.2 \times 10^{-4}\Delta t\ \$/(\text{hr.})(\text{sq.ft.})$$

With incremental surface at $3.00/sq.ft. the charges are:

$$3 \times 4.68 \times 10^{-5}\ \$/(\text{hr.})(\text{sq.ft.})$$

Equating these incremental charges, it is found that $\Delta t = 66°$ F.

Usually problems of this type are more complicated involving costs for fluid pumping and countercurrent flow of fluids which change in temperature. It is only when one of the media is at constant temperature or for parallel flow heat exchange that it can be assumed, as above, that the final square foot exchanges heat at the outlet temperature difference. Such references as Perry's handbook (*4*) consider these cases, but do not give details for the methods which should be used for incorporation of a profit item into the economic balance. The equations developed here may be readily applied.

TABLE 3.—EVALUATION OF COST

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
N	E	F, Total Steam Rate M lb./hr.	Increase in Steam Rate M lb./hr.	C_F	C_A	$\frac{C_F+C_A}{F}$	Avg. Cost for Steam $/M lb. (7)÷(3)	Increase in C_F+C_A $/hr.	Incidental Cost for Steam $/M lb. (9)÷(4)
100	76	51.8	....	16.7	8.4	25.1	0.49	....	....
150	76	77.8	26.0	24.8	8.7	33.5	0.43	8.4	0.32
175	75	90.9	13.0	29.3	9.0	38.2	0.42	4.7	0.36
200	74	103.8	13.0	33.9	9.0	42.9	0.41	4.7	0.36
225	70	116.8	13.0	38.3	9.4	47.6	0.42	5.7	0.44
250	69	129.8	13.0	42.8	9.6	52.1	0.43	7.5	0.57
275	65	143.0	13.0	48.2	10.0	63.2	0.44	7.1	0.55
300	61	155.6	13.0	61.6	10.3	72.1	0.46	8.9	0.68

From the above table the optimum rating will be at 225–250% of nominal rating, column (10).

This may be compared with the solution given by McAdams, column (8), where it is assumed that the optimum will be given by the condition corresponding to minimum total cost of fuel plus "fixed charges." While the figure of 200% is not far different, it will be appreciated that by varying the basic assumptions regarding cost of the new installation widely different results could be obtained. To agree with the method proposed here it would be necessary for the "fixed charge" specified to include a profit item. Also it would be necessary to assume that the proposed new boiler installation would produce steam at substantially the same cost (including profit allowance in the "fixed charge" item) as the existing installation.

Summary

It is apparent that designing plants in which the methods developed above are used will be equivalent to specifying that the last increment of investment shall yield some predetermined satisfactory return. What constitutes a satisfactory rate of return depends on a number of factors such as risk and availability of capital. Whether the selected return rate is determined by an engineering department or the management, such a figure must be available to the designing engineer if he is to arrive at a selection of sizes and conditions which will constitute an optimum.

In design calculations care must be exercised to make due allowance for items other than rated plant capacity, such as flexibility and safety. Equipment designed on the above basis may often be found to have less overload capacity than that in which auxiliaries are selected on a minimum cost basis. However, it is believed that if overload capacity is desirable, it should be incorporated as a part of the original design specifications. The same considerations apply in the case of safety factors. Extra corrosion allowances, spare pumps, etc., can be specified in the design with due regard for the risk involved in physical failure and the effect of such failure on profit.

Thus, while in the past, values and taxes were more stable than at present, it is now found that customary methods for judging the attractiveness of new ventures often require some revision to keep up with the changing economic picture. It is hoped that the method presented here will be a step in the direction of a more flexible viewpoint in the selection and design of such process equipment.

Notation

(Note the nomenclature used only in specific problems is not represented here.)

$a,b,c \ldots n$ = variables in the profit equation (*see* Eq.(7))

C = cash position, increase in company assets after y years of operation of venture(*see* Eq.(5)), $

I = investment in a venture, $

i = fixed charges proportional to investment which enter into the gross earnings, such as maintenance (but not including depreciation), expressed as fraction

O = operating earnings = $R + iI$, gross earnings before deduction of charges which are directly proportional to investment, $/year

P = net profit from a venture after all deductions for taxes and depreciation, $/year

p = net rate of profit on investment, expressed as per cent/year

p_A = minimum acceptable net profit on investment from a risk venture, expressed as per cent/year

R = gross earnings from a venture, $; sales realization less raw materials costs, operating costs, maintenance costs, insurance, social security, unemployment taxes, etc., but before deducting income tax and depreciation

T = payout time, I/R by usual definition, years

T_A = maximum acceptable payout time on investment for risk ventures, years

V = venture profit (*see* Eq. (3)), $/year

Y = time of operation for computing cash position, years

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Discussion

Sidney Lee (Dallas Associated Laboratories, Dallas, Tex.): It seems that the rate of return on investment is evaluated without taking into consideration the factor of time. In other words, a dollar return obtained three, four and five years from now is considered more or less equivalent to a dollar return the first year so that percentage return of 25% by 10 or 15 years from now is considered in the same general light as the equivalent percentage return in the first year. Also, in many venture fields, the dollar return will vary year to year and what should be considered is the present value of the future dollar of return. For example, a petroleum company engaged in marketing might construct a service station in an area, the population of which was going to expand so, with some degree of accuracy or at least with some hope of accuracy, it would calculate the gross profit and the gross income which would change from year to year and have a graph to that effect; so also might a person putting in a retail store or a theatre or perhaps a pipeline which wasn't at capacity at initial construction. This factor is probably most important in crude oil production when you know your production in the second, third, fourth and fifth year will be different from the first. Have you considered the present value of the future dollar and worked out a program whereby you could, using all those additional factors, come out with a rate of return? For example, if a company ventured $1,000,000 in a project, taking all those factors into account, you might say that his net return would be 3% or 8% or 4% on a long-range period of time by using the compound interest table, and then he could contrast the possibilities of investing this money in this plant or putting it to some other use, such as retiring a preferred stock or retiring bonds or investing in a nonmanufacturing operation?

John Happel: Two simplifying assumptions have been made in the development of the formulas presented here as regards the time element. First, it is assumed that the entire return will be withdrawn immediately as it accrues, rather than being reinvested at compound interest. Secondly, it is assumed that the rate of return will remain constant over the entire period of the venture. By modifying these assumptions a more complicated but more accurate form could be obtained which as you suggest might be more useful for certain purposes.

Compound interest is important in any long-time proposition where a relatively low rate of return is obtained with a high degree of certainty. This is the case with savings bank deposits and insurance payments. In ventures where a high rate of return over a short time is necessary because of the high risk

involved, it is often not worth while to introduce the additional complication of compound interest.

Regarding the second assumption, if the future can be accurately predicted it will be possible to calculate readily the return over a period of time using appropriate rates of return which vary with time, and if desired also include allowance for reinvestment of any portion of the return at compound interest. Qualitatively, it is certainly true that earnings in many cases will vary with time. For example, it often takes a number of years for a proposition to be developed from the research stage to a full-scale profitable commercial venture. Again, even when capital is invested in a proposition of proved value, it will take a period of time to erect a plant and get it operating smoothly, during which time no return is being realized.

The accurate prediction of rates of return over a period of time is more difficult than their qualitative appreciation. In some cases, which you have described accurate prediction of future return is possible and, of course, should then be taken into consideration.

In other cases, prediction is more difficult. For example, I have recently been interested in the economics of ethyl alcohol manufacture from ethylene. The price of alcohol has fallen sharply during the past year in a way that would be difficult to predict quantitatively and this circumstance naturally has a marked effect on the economics of alcohol production.

Sidney Lee: In certain venture possibilities, it is obvious that the future must be taken into consideration. If you are developing an oilfield and, starting from the day you are drilling one well, you have a program for future drilling and production. In other ventures where changes in prices, etc., are unpredictable, these can be included as parameters in a suitable chart.

Frank J. Smith (Pan-American Chemical Co., New York, N. Y.): I think I have a serious objection to the figure showing payout data. You have divided your investment costs by indicated gross profits in order to obtain payout time. You have failed to consider taxes as an operating cost and if you had deducted taxes so as to leave you a net profit and had divided the investment cost by the net profit to obtain a payout you would have obtained an orientation between cases 1, 2 and 3 which is different from the orientation you have shown in the paper. It is interesting to note that this revised orientation would have agreed with that obtained as a result of your suggested method of calculating payout.

John Happel: Sometimes payout time is modified to allow for the effect of taxes, but such variations still do not make allowance for a minimum acceptable profit on investment.

Raphael Katzen (Vulcan Copper & Supply Co., Cincinnati, Ohio): Dr. Happel's emphasis on the effect of taxes and depreciation on net profit and payoff is commendable and the fact is emphasized that these costs affect adversely many projects. However, I believe there are certain projects in which these current factors are actually an aid. I would like Dr. Happel's comments particularly on waste disposal units where there are no operating profits to balance against investment, and where the operating costs have to be minimized as a result. There is a possibility that you can apply operating costs of waste disposal units where there is no credit against operating costs of the complete plant and thereby reduce your present taxation. Do you think the formula could be applied in reverse, crediting tax savings?

John Happel: As you point out, waste disposal operations would be conducted only in conjunction with other operations which are profitable in any commercial venture. An over-all greater profit would be the only economic justification for more expensive waste disposal equipment and it seems to me that this additional expense would be evaluated in the same way as any other incremental equipment investment. I do not believe that higher taxes would have any effect other than to discourage venture capital investment including that invested in all necessary auxiliaries such as waste disposal facilities.

Anonymous: Where, in these equations, does the cost to the company of using its own money appear? If we were going to float a stock issue the cost of this money would certainly be different from a bond issue or debenture.

John Happel: The minimum acceptable return on any investment involves items of both risk and availability of capital. The management, for any given proposition, will have to get additional capital in some way which will vary depending on the financial structure and policy of the company. I am assuming that the management, for any particular proposition and at a given time will have in mind the risk involved and will be able to state that the proposition which an engineer is asked to evaluate will not be attractive to it below a certain figure. No attempt is made here to analyse how that figure is arrived at by management.

Anonymous: Could you have a duplicate set of curves; one for stocks and one for bonds?

John Happel: Such a scheme could be developed. I think a capable accountant working with engineers should be able to accomplish much along the lines you suggest.

Ovid Baker (Magnolia Petroleum Co., Dallas, Tex.): This economic approach to design is a desirable one. However, there is another economic angle to it. Let us assume that a chemical engineer designs a plant in the ordinary fashion, without making these economic balances on all the heat exchangers, insulation, etc., and the plant looks good to make $1,000 per day profit. It may take him three weeks to go back and calculate all these economic balances for this plant. This may delay the plant start-up three weeks and cost $21,000 profit. If the probable savings do not exceed $21,000 there is no payout in making the more detailed economic analysis.

John Happel: Time spent in engineering calculations whether on design or economics will involve a delay in the date of plant operation and realization of the profit expected. Certainly needless refinement in calculations is not justified. However, often engineering design calculations are far more complicated than those proposed here. For instance, I have seen calculations that take a week for determination of the number of trays in a single bubble tower. Most calculations I have talked about here won't take more than a few hours to do. The determination of optimum heat exchanger capacity and insulation thickness, for example, does not usually require a great amount of time.

Paul R. Schultz (Standard Oil and Gas Co., Tulsa, Okla.): We have found it necessary to compute the net profit and payoff of a proposed plant on a year-by-year basis. This is due to three factors, viz., variations in yearly production, variations in forecast prices, and the effect of paying income taxes in the succeeding year. Since we always determine payoffs after income taxes, this last factor cannot be overlooked even in an ideal case of constant production and price. Further, when you do not have the ideal case of constant production and price, we feel that it is necessary to have another index of evaluation. We use the ratio of net profit, for the total plant life, to investment cost. With these two indexes, plants can be easily compared.

John Happel: Use of forms of payout time and cash position together as you suggest rather than employing either one alone as an index has advantages. The only difficulty in employing two indexes is to decide what relative importance or weight to give each one in arriving at a decision. The method proposed in this paper is a way of combining these concepts into one index.

(Presented at Eleventh Regional Meeting, Tulsa, Okla.)

FIRST INSTITUTE LECTURE

Last year at Pittsburgh members of the A.I.Ch.E. heard William H. McAdams, professor of chemical engineering at Massachusetts Institute of Technology give the First Institute Lecture. This distinguished educator instituted the first of this annual series of reviews in unit operations with a panoramic view of Heat Transfer. Chemical Engineering Progress is proud to publish here the full text of this talk which covers the fundamentals of the several types of heat transfer, summarizes recent developments, and outlines needs for further work

HEAT TRANSFER

WILLIAM H. McADAMS

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THE mechanism of heat transfer by steady unidirectional conduction is given by the simple relation of Fourier (*37*) proposed in 1822:

$$q_k = -kA\frac{dt}{dx} \qquad (1)$$

where

q_k is the rate of heat conduction along the x-axis, A is the cross section of the path, normal to the x-axis,

$-dt/dx$ is the temperature gradient along the path,

k is the thermal conductivity, a physical property of the substance.

This equation is well established for conduction in homogeneous isotropic solids, and practical application of the equation to various problems requires (*a*) laboratory measurement of thermal conductivity of a representative specimen, (*b*) solution of the equation for the particular geometric and boundary conditions.

Steady Conduction. For many complex shapes encountered with steady flow in finned (extended) heating surfaces, Gardner (*38*) gives analytical solutions in both algebraic and graphical form. More complex cases, as with two-dimensional conduction, can be solved by the mapping method of Lehmann (*54, 2*), wherein isotherms and adiabatics intersect to form curvilinear squares. Alternatively, the relaxation procedure of Emmons (*31, 28a, 80*) may be used. Unusually complex cases can be solved experimentally by means of one of several types of electrical models; a good review of these is given by Jakob (*49*). The membrane analogy or soap-film technique (*98*) is also available.

Transient Conduction. For transient problems, where the temperature varies with both location and time, analytical solutions are available in both algebraic and graphical forms for restricted boundary conditions. A number of books (*5, 13, 48, 49*) devotes many pages to the mathematics of heat conduction. More complex and less restricted cases can be solved by the numerical methods of Dusinberre (*28, 28a*), which cleverly substitute arithmetical operations for the calculus. Although these are approximation methods, by permitting the removal of false restrictive assumptions, they can lead to more accurate answers than the so-called exact, analytical procedures. For a problem which can be solved by both methods, these numerical methods give good agreement with the analytical methods. The electrical analogy method has numerous applications (*3, 5, 43, 84, 86*). It has recently been found (*10*) that the heating of granular settled solids, while flowing downward through a vertical heated tube, can be predicted by the theoretical equation for rod-like flow, upon assuming that the heat is transferred only by radial conduction; this is the same equation as derived in 1883 by Graetz (*41, 24*).

Thermal Conductivity of Gases. Recent measurements (*51a*) of the thermal conductivities of steam (up to 150 atm. and 660° F.) are considerably lower than the Russian data previously available, and values of k for air and engine-exhaust gas have been measured (*7*) up to 900° F.

In résumé, since the mathematics of heat conduction is well understood, problems in conduction in homogeneous solids may be solved by existing techniques. Future experimental work should involve measurement of physical properties of present materials over wider ranges of conditions, and of new materials which will be developed in the future. It will be necessary to devise methods of measuring thermal conductivities at temperatures up to 5000° F. Additional work is needed on the thermal conductivities of solids, gases and liquids. Further study of the mechanism of heat transfer in porous solids seems warranted, because of the internal transfer by conduction, radiation and convection.

Thermal Radiation

The basic equation for total thermal radiation from the ideal radiator (the "black body") was discovered empirically by Stefan (*96*) in 1879 and was derived theoretically by Boltzmann (*9*) in 1884:

$$q_r = \sigma A T^4 \qquad (2)$$

where

- q_r is the rate of heat transfer by radiation, from one side of the "black" surface of area A,
- T is the absolute temperature of the surface, and
- σ is the Stefan-Boltzmann constant.

The situation was further clarified in 1900 when Planck (*87*) proposed the relation between the monochromatic intensity $W_{B\lambda}$ and the wavelength λ of the radiation, integration of which gave the Stefan-Boltzmann Law, (Eq. 2). The cosine law is also well established for black surfaces, and integrations of the direct exchange between black bodies give relations of the form

$$q_{net,direct} = \sigma A_1 F_{12}(T_1^4 - T_2^4) \qquad (3)$$

The purely geometrical factor F is a measure of how well one surface sees another, and values of F are given by equations and charts (*45*) in terms of the appropriate dimensionless ratios (diameter over clearance for parallel opposed squares).

In a complete enclosure, the net radiation consists of the direct radiation from source to sink, plus the indirect radiation (from the source to adiabatic refractory, and thence to the sink). The corresponding equation for the total radiation in the all-black system is:

$$q_{net,total} = \sigma A_1 F'_{12}(T_1^4 - T_2^4) \qquad (4)$$

The factor F'_{12} is available for a number of geometrical arrangements, and usually exceeds F. A useful relation is that the sum of all F factors, for each surface, equals 1:

For A_1:

$$F_{11} + F_{12} + F_{13} + \ldots + F_{1n} = 1 \qquad (5)$$

For A_2:

$$F_{21} + F_{22} + F_{23} + \ldots + F_{2n} = 1 \qquad (5a)$$

Obviously, flat or convex surfaces cannot see themselves, in which case, F_{11} and F_{22} are zero.

With grey surfaces (which have emissivities less than the black body) the net radiation is less than with black bodies and can be estimated by simple equations developed by Hottel (*45*):

$$q_{net,total} = \sigma A_1 \mathcal{F}_{12}(T_1^4 - T_2^4) \qquad (6)$$

$$\frac{1}{\mathcal{F}_{12}} = \frac{1}{F'_{12}} + \frac{1}{\epsilon_1} - 1 + \frac{A_1}{A_2}\left(\frac{1}{\epsilon_2} - 1\right) \qquad (6a)$$

Evaluation of the total heat transferred in a combustion chamber containing heat-receiving surfaces is difficult, since it involves heat transfer by convection from gases to surfaces, radiation between surfaces, and radiation from certain polyatomic gases (such as water vapor and carbon dioxide) and the surfaces.

In résumé, the transfer of heat by radiation between surfaces in transparent media is on a sound mathematical basis. In the combustion of fuels with preheated air in industrial furnaces at high temperatures, various chemical compounds (OH, CO and NO) of unknown radiating characteristics are formed (*46*). Since reaction rates and nature of the products depend on flame temperature, and since flame temperature is dependent on heat transfer, further studies seem imperative. Gas radiation data for steam and carbon dioxide are limited to low pressures, and the effect of high pressure should be determined. Since a number of applications now involves combustion of fuels with oxygen-enriched air or oxygen instead of air, emissivities of surfaces and combustion products will be needed at unusually high temperatures. Suggestions for further work are summarized in Table 1.

Convection

In 1701 Newton (*79*) defined the heat-transfer rate q_c from a solid surface to a fluid by the equation

$$q_c = h_m A(t_w - t) \qquad (7)$$

where

- A is the area of the surface in contact with the fluid at bulk temperature t,
- t_w is the temperature of the surface, and
- h_m is the coefficient of heat transfer from surface to fluid, excluding any radiation.

For conduction in solids, and for radiation through transparent media, the mechanisms are known and the heat-transfer equations are dependable. With heat transfer from a solid to a fluid, the situation is far more complex, and in fact Equation (*7*) should not be considered a law, but merely a definition of the mean coefficient of heat transfer.

Heating or Cooling without Change in Phase

1. *Turbulent Flow in Tubes.* In the limiting case of isothermal flow of a liquid or gas in turbulent motion inside a long straight tube with well-developed flow, radial exploration of local velocity suggests three distinct zones, as shown in Figure 1 (*62*): (1) a turbulent zone BC in the central portion or core, in which eddies are always present, (*2*) a "buffer-layer" AB in which eddies are sometimes present and are subsequently replaced by streamline flow, and (3) a laminar sublayer OA next to the wall, in which eddies are absent. The evidence of both the laminar sublayer and the buffer layer is inconclusive (*75*) for turbulent flow in a tube, although laminar flow has been shown to prevail in the sublayer on a flat plate (*100*). In the laminar sublayer, heat transfer is by molecular transport (conduction) while in the buffer layer and turbulent core the warmer portions of the fluid are mechanically mixed with colder portions by eddy diffusion (convection).

A sound theoretical approach in predicting h is hampered by lack of knowledge of the effect of radial temperature gradient upon velocity gradient. The latter is due to momentum diffusion towards the wall. The ratio of the molecular diffusivity of momentum (μ/ρ) through the laminar sublayer, to the molecular diffusivity of heat $(k/\rho c_p)$ is

$$\frac{\mu/\rho}{k/\rho c_p} = \frac{c_p \mu}{k} = \text{Prandtl modulus} = N_{Pr}$$

Figure *2* shows the temperature and velocity fields in dimensionless form, as predicted by Martinelli (*72*) from analogy between the transfer of heat and momentum. It will be recalled that the velocity field depends only on the Reynolds number $(DV\rho/\mu)$. Hence for a given Reynolds number, the velocity distribution is fixed, as shown in Figure *2*, by the curve of u/u_1 vs. reduced distance from the wall, y/r_w. The temperature field depends on the Prandtl number, as shown in Figure 2. For the special case where these two molecular diffusivities are equal, the Prandtl modulus is 1, and the temperature and velocity fields are theoretically identical (Fig. *2*). Since the Prandtl modulus for common gases is nearly 1, mathematical relations between the transfer of heat and momentum are simple, and fairly reliable for incompressible flow:

$$\frac{h_m}{c_p G} = \frac{f}{2} \qquad (8)$$

or

$$\left(\frac{S}{A}\right)\frac{(t_2 - t_1)}{(t_w - t)_m} = \frac{0.023}{(DG/\mu_f)^{0.2}} \qquad (8a)$$

For other fluids the Prandtl numbers may be very small (0.006 ca. for a molten mercury) or 100 or more for a viscous hydrocarbon oil. Analogies between the transfer of heat and of momentum are based on inadequate data as to the mechanisms, and the simplifying assumptions that the velocity field with heat transfer is the same as for isothermal flow, and the physical properties are independent of temperature. The resulting theoretical equation of Martinelli (*72*) involves the following six dimensionless groups:

a: $\frac{h_m}{c_p G}$ Stanton modulus

b: $\frac{DVp}{\mu}$ Reynolds modulus

c: $\frac{c_p \mu}{k}$ Prandtl modulus

d: f, Fanning friction factor, which equals the shear stress τ_o at the wall, divided by $\rho V^2/2g_c$:

$$f = \frac{\tau_o}{\frac{\rho V^2}{2g_c}}$$

e: $a_e/(a_e + a_m)$, the ratio of the thermal diffusivity by eddy transport, to the sum of the diffusivity by both eddy and molecular transport, and

f: $(t_w - t_a)/(t_w - t_m)$, the ratio of the maximum temperature difference to the mean value.

In using the analogy equation, the friction factor f is graphically related to the Reynolds number, the diffusivity ratio is graphically related to both the Reynolds modulus and the product of the Reynolds modulus and the Prandtl modulus, and the temperature-drop ratio is related to the moduli of both the Reynolds and Prandtl. Thus only three dimensionless ratios (Stanton, Reynolds and Prandtl) are controlling. Despite the assumptions made, the Martinelli equation predicts heat-transfer coefficients of the right order of magnitude, which is encouraging. The analogies have the advantage over the wholly empirical equation in showing how the radial distribution of temperature depends on the Prandtl number. Figure 2 from the 1946 Martinelli analogy (*72*) for a Reynolds modulus of 10,000, shows that 95% of the temperature drop occurs in the laminar sublayer for a heavy oil, compared with roughly 3% for liquid mercury. It will require an extensive research program to put these analogies on a firm physical foundation.

In practice designers employ empirical equations (*19, 12*) containing the three basic dimensionless moduli of the theoretical equations, and sometimes include (*95, 12*) a weak function $(\mu_w/\mu)^{0.14}$ of the ratio of the viscosities at the wall and bulk temperatures (*12*):

$$\left(\frac{h_m}{c_p G}\right)\left(\frac{c_p \mu_f}{k}\right)^{2/3} = \frac{f}{2} = \frac{0.023}{(DG/\mu_f)^{0.2}} \qquad (9)$$

or

$$\left(\frac{h_m}{c_p G}\right)\left(\frac{c_p \mu}{k}\right)^{2/3}\left(\frac{\mu_w}{\mu}\right)^{0.14} = 0.027\left(\frac{DG}{\mu}\right)^{-0.2} \qquad (9a)$$

Compressible Flow. Consider adiabatic flow of a compressible fluid (air) at high velocity through a tube of constant diameter. As the air flows down the tube the absolute pressure decreases, owing to friction and increase in kinetic energy, and the temperature of the moving stream must decrease to satisfy the total energy balance. Under the influence of the radial gradient in velocity, momentum is transferred towards the wall, tending to heat the wall. But be-

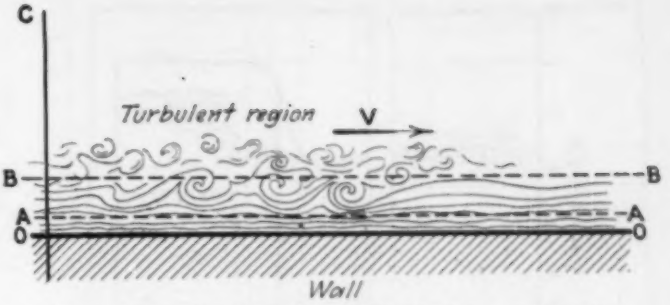

Fig. 1. Isothermal turbulent flow of fluid parallel to a surface (*62*).

TABLE 1.—NEEDS FOR FURTHER WORK ON FURNACES AND COMBUSTION CHAMBERS

1. Gas Radiation
   a. Calculation of total radiation from fundamental molecular constants, and testing against CO_2, H_2O, CO.
   b. Measurements on H_2O and CO_2 at high pressures.
   c. Calculations for CO, OH, NO, CO_2, H_2O at high temperatures.
2. Emissivities of Surfaces at High Temperatures
3. High Temperature Combustion Chambers
   a. Integration of progress of combustion, heat transfer and fluid flow.
   b. Production of luminosity in flames.

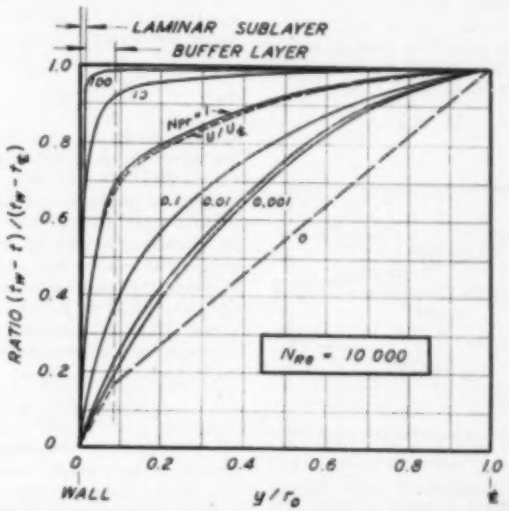

Fig. 2. Radial distribution of temperature in a tube, according to the Martinelli (*72*) analogy between the transport of heat and momentum. Velocity distribution for turbulent flow is shown for comparison. For N_{Pr} of 1 ($c_p\mu/k$ of 1) it is seen that the temperature and velocity fields are substantially identical. (Courtesy Am. Soc. Mech. Engrs.)

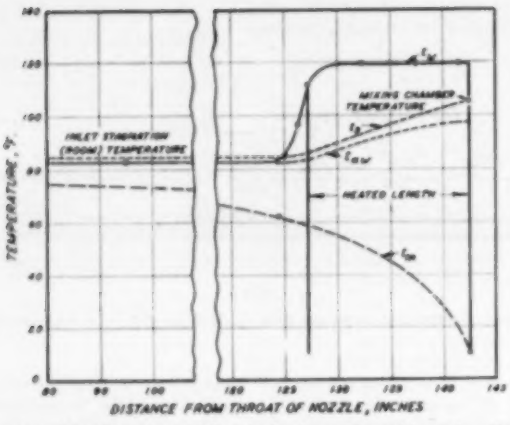

Fig. 3. Results of heating air at high velocity in a tube, with sonic velocity at the outlet. Despite heat transfer sufficient to increase the stagnation temperatures some 20° F., the temperature of the moving stream fell some 50° F. McAdams, Nicolai and Keenan *(70).*

cause of the ideal external insulation, this energy must diffuse back into the stream under the influence of a temperature potential. Consequently the adiabatic wall assumes a temperature t_{aw} higher than the moving stream, by an amount depending primarily on the ratio of the molecular diffusivity of momentum to the molecular diffusivity of heat. The conventional Δt (wall temperature less bulk temperature of the stream) is finite, but the heat-transfer rate q through the wall is zero. Under these conditions, the conventional equation ($q = h A \Delta t$) has no utility. This dilemma is solved by defining a new potential, the "effective" temperature difference *(29, 32, 70)*:

$$t_w - t_{aw}$$

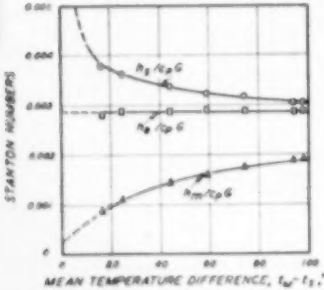

Fig. 4. Comparison of three Stanton moduli, defined in terms of three temperature potentials:

$$h = \frac{dq/dA}{t_w - t}; \quad h_e = \frac{dq/dA}{t_w - t_{aw}}; \quad h_s = \frac{dq/dA}{t_w - t_s}$$

McAdams, Nicolai, and Keenan, *(70).*

which is zero when the heat transfer through the wall is zero. If the wall temperature t_w is raised above t_{aw}, heat is transferred according to the equation

$$dq = h_e(dA)(t_w - t_{aw}) \qquad (10)$$

Figure 3 *(70)* shows results of a heat-transfer run with a mass velocity of 43,500 lb. of air/(hr.)(sq.ft.). Air entered at room temperature and the wall temperature in the test section was maintained at 120° F. by means of condensing steam. Although enough heat was transferred through the wall to increase the stagnation temperature

$$t_s = t + \frac{V^2}{2g_c J c_p} \qquad (11)$$

by some 20° F., the temperature of the moving stream of air fell roughly 50° F. (from 60° F. to 10° F.). Figure 4 summarizes results of a number of heat-transfer runs. The effective heat-transfer coefficient (expressed in terms of the Stanton number, h_e/c_pG) is seen to be independent of temperature potential, while that based on the conventional Δt is not. When a coefficient is based on the excess of the wall temperature over the stagnation temperature:

$$dq = h_s(dA)(t_w - t_s) \qquad (12)$$

the corresponding heat-transfer coefficient h_s is more nearly independent of temperature potential than the coefficient h_w. The recovery factor, N_r, defined as

$$N_r = \frac{t_{aw} - t}{t_s - t} = \frac{t_{aw} - t}{V^2/2g_c J c_p} \qquad (13)$$

relates the three temperatures, and for subsonic flow of air is roughly equal to the square root of the Prandtl number *(29, 32)*:

$$N_r = \sqrt{\frac{c_p \mu}{k}} \qquad (14)$$

A recent paper *(47)* reports results for heating air with unusually high Δt. Skin temperatures have been measured *(81)* on a *V-2* rocket in supersonic flight. Another *(67)* reports data for superheating steam at pressures from 100 to 3500 lb./sq.in.abs. with Δt from 100 to 624° F. Results were correlated in terms of four dimensionless ratios:

$$\frac{hD_e}{k_f}\left(\frac{c_p \mu}{k}\right)_f^{-1/3} = 0.021\left(1 + \frac{2.3}{L/D_e}\right)\left(\frac{D_e G}{\mu_f}\right)^{0.8}$$

wherein the new values *(51a)* of k were employed.

Several examples may be cited of cases where heat-transfer coefficients for heating or cooling may be predicted fairly well with mathematical theory.

2. Streamline Flow of Liquids Inside Tubes. Here it is assumed that well-developed streamline flow prevails (consequently the velocity distribution is parabolic and independent of the Reynolds number), and that heat is transferred only by radial conduction. The resulting theoretical equation of Graetz *(40)* needs empirical correction *(19, 95)* for the fact that physical properties are a function of temperature, thus distorting the velocity field *(95)*:

$$\left(\frac{h_a D}{k}\right)\left(\frac{\mu_w}{\mu}\right)^{0.14} = 2.0\left(\frac{wc_p}{kL}\right)^{1/3} \qquad (15)$$

For a fluid with a given coefficient of expansion, Martinelli et al *(73)* showed that direction of flow in a vertical pipe will affect the heat-transfer coefficient, and that a vertical pipe will give larger coefficients than a horizontal pipe when the natural convection velocity near the wall of the vertical pipe is in the same direction as the forced flow. The quantitative relations between the appropriate dimensionless groups were given in graphical and algebraic form, and predict results somewhat more closely than does Equation (15).

3. Laminar Flow Along a Flat Plate, without Phase Change. Upon assuming laminar flow along the plate at uniform temperature, Pohlhausen *(88)* obtained theoretical equations for both the local

coefficient at the length x, and the mean coefficient from x of 0 to x of L:

$$\left(\frac{h_{x1}}{c_p V_x \rho_x}\right)\left(\frac{c_p \mu}{k}\right)^{2/3} = \frac{1}{3}\left(\frac{x V_x \rho_x}{\mu}\right)^{-1/2} \tag{16}$$

$$\left(\frac{h_{m1}}{c_p V_x \rho_x}\right)\left(\frac{c_p \mu}{k}\right)^{2/3} = \frac{2}{3}\left(\frac{L V_x \rho_x}{\mu}\right)^{-1/2} \tag{16a}$$

Both the local and mean coefficients are defined in terms of the initial temperature difference, $t_w - t_1$. In a recent thesis (*51*) it was shown that this theoretical equation of Pohlhausen correlates data (*16, 51*) for laminar flow of air in steam-heated tubes, for L/D from 5 to 63, as shown in Figure 5. This agreement is somewhat fortuitous, since the local coefficient decreased with increase in length for only 42 diameters (instead of 63) and the theory did not take into account the change in velocity of the main stream due to the reduced velocity of the laminar layer on the inner wall of the tube.

4. *Local Coefficients.* In many other cases, the point or local coefficient of heat transfer

$$h = \frac{dq/dA}{t_w - t} \tag{17}$$

changes substantially from one location to another. In such cases measurements of local coefficients yield much more useful information than mean coefficients. A few cases may be cited.

a. Inlet Region of a Tube. For turbulent flow in a tube, the local coefficient of heat transfer is a function of length in the inlet region (*8, 16*). At the length at which the velocity profile ceases to change, the flow is fully developed and the local h is independent of length. Value of L/D at which the flow becomes fully developed depends (*8*) on the type of entry and the Reynolds number, DG/μ.

According to the theory of Latzko (*53a, 8*) for turbulent flow in a tube with a bellmouthed entry, laminar boundary layers build up on the wall in the inlet region of the tube, and meet at the "critical," or "starting length," given by:

$$\left(\frac{L}{D}\right)_c = 0.693\left(\frac{DG}{\mu}\right)^{1/4} \tag{18}$$

Thus for DG/μ of 40,000, the predicted starting length is 9.8 diameters.

For L/D less than given by Equation (18), Latzko (*53a, 8*) predicts that the mean coefficient h_m (from L of 0 to L) is related to the asymptotic value h_∞ by the equation:

$$\frac{h_m}{h_\infty} = 1.11\left[\frac{(DG/\mu)^{1/5}}{(L/D)^{4/5}}\right]^{0.275} \tag{19}$$

This prediction is closely substantiated by recent data (*8*) for a bellmouthed entry.

For L/D greater than given by Equation (18), Latzko predicts

$$\frac{h_m}{h_\infty} = 1 + \frac{C}{L/D} \tag{20}$$

where the dimensionless factor C is a weak function of DG/μ:

$$C = 0.144\left(\frac{DG}{\mu}\right)^{1/4} \tag{21}$$

This prediction is confirmed by recent data (*8*) for a bellmouthed entry, with DG/μ of 26,000 to 56,000, where C was found to be 1.4 compared with 1.83 to 2.22 predicted by Equation (*21*). For L/D of 10, a substantial change in C produces only a small change in h_m/h_∞.

Table 2 gives experimental values (*8*) as a function of the type of entry.

b. The finned passages for air flow around an air-cooled engine cylinder (*27, 66*).

c. Flow normal to single tubes (*4, 26, 33, 34, 39, 44*)

d. Natural convection from vertical plates (*42, 91*)

TABLE 2.—VALUES OF C (8) FOR DG/μ FROM 26,000-56,000 FOR L/D > 5

Bell mouth with one screen	1.4
Long calming section ($L_e/D = 11.2$)	1.4
Short calming section ($L_e/D = 2.8$)	ca. 3.0
45° angle bend entrance	ca. 5.0
90° angle bend entrance	ca. 7.0

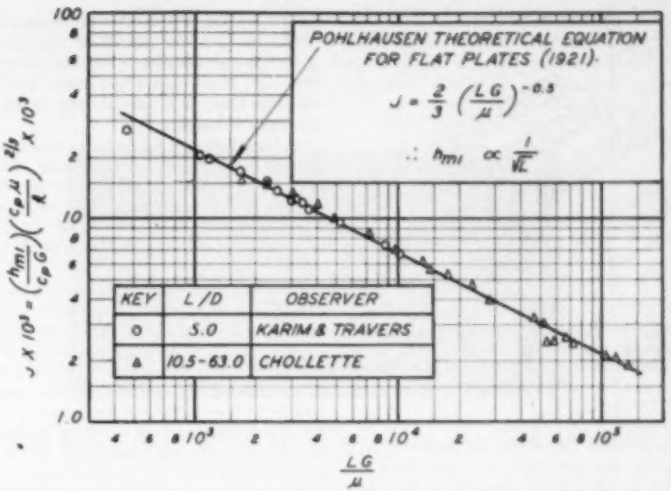
POHLHAUSEN THEORETICAL EQUATION
FOR FLAT PLATES (1921)
$J = \frac{2}{3}\left(\frac{LG}{\mu}\right)^{-0.5}$
$\therefore h_{ml} \propto \frac{1}{\sqrt{L}}$
KEY | L/D | OBSERVER
○ | 5.0 | KARIM & TRAVERS
△ | 10.5-63.0 | CHOLLETTE
$J \times 10^3 = \left(\frac{h_{ml}}{c_p G}\right)\left(\frac{c_p \mu}{k}\right)^{2/3} \times 10^3$
$\frac{LG}{\mu}$

Fig. 5. Correlation of Karim and Travers (*51*) of data (*16, 51*) for laminar flow in heated tubes, by theoretical equation of Pohlhausen (*88*) for laminar flow along a heated flat plate.

5. *Experimental Analogies between Transfer of Mass and of Heat.* Since equations for mass transfer are of the same forms as those for heat transfer, it would be expected that mass transfer can be used as an experimental analogue for heat transfer. This proves to be the case, as shown in Figure 6 for flow normal to single tubes (*101*). The curve marked "author" was obtained by Winding and Cheney (*101*) for the local rate of evaporation of naphthalene into air.

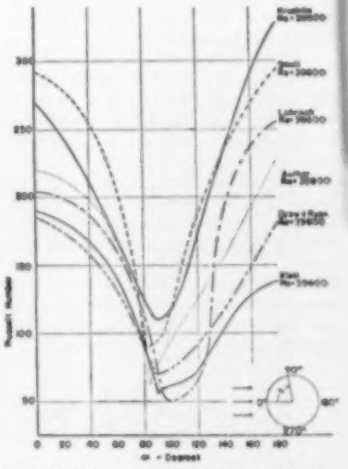

Fig. 6. Comparison of local Nusselt numbers for transfer of heat or mass for air flowing normal to a cylinder. Data marked "author" are by Winding and Cheney (*101*) for evaporation of naphthalene. (Courtesy Ind. Eng. Chem.).

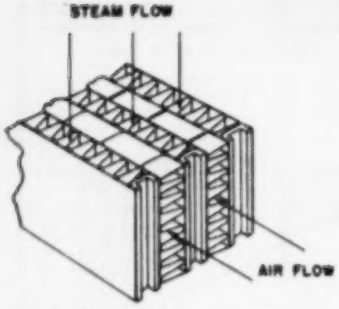

Fig. 7. Compact heat-exchanger containing draped brazed fins, tested by London et al *(60)* (Courtesy Bur. Ships, Navy Dept.).

Some other curves are for heat transfer, while the rest are for mass transfer. Curves of similar shape have been obtained for heat transfer by other workers (*4, 26, 33, 34, 39, 44, 93*).

For turbulent flow in tubes, recent work (*59, 71*) on mass transfer has extended the Schmidt modulus to 3000, compared with a Prandtl modulus of 100 for heat transfer. Since the Schmidt number for mass transfer is analogous to the Prandtl number for heat transfer, this finding extends our ability to predict heat transfer at high Prandtl numbers. Data for both mass and heat transfer were correlated (*59, 71*) in terms of Equation (9) (*13, 10a*). It should be pointed out that these analogues between the transfer of mass and of heat have the limitation that a mass-transfer analogue cannot be devised to simulate a heat-transfer case with a large temperature potential.

6. *Compact Heat-Exchangers.* During the recent war airplanes required heat exchangers having a large heat-transfer surface in relation to the volume and weight of the exchangers. These were fabricated in a variety of forms, usually involving thin-walled passages heavily finned with thin metal sheets giving a large heat-transfer surface (Fig. 7). In some cases the heating surface was subdivided into short strips to interrupt the boundary layer and thus secure the advantage of a high coefficient of heat transfer as predicted by the Pohlhausen theoretical equation (*88*). In fact, the empirical equation of Norris and Spofford (*82*) for pin or strip fins, involving a perimeter Reynolds number, is a special case of the Pohlhausen equation.

A triple-passage exchanger, containing finned surfaces, has been used (*23, 99*) in a reversing exchanger in an oxygen plant. Some data are available for packed beds (*56, 58*), packed regenerators and for fluidized solids (*74, 57*).

7. *Selection Methods.* Assuming that several arrangements of heat-transfer surface may be used, the designer wishes to select that type best suited to the proposed application. If there are no restrictions on dimensions and weight of the exchanger, minimum cost for fixed charges and pumping power will be the criterion, which may be expressed in terms of an optimum velocity (*64*), or the corresponding optimum power loss per unit surface (*21*). Romie (*90*) discusses the criteria when other factors are important, such as dimensions and weight.

8. *Transpiration Cooling.* In some cases, the main objective of heat transfer is to keep some surface cool, while in contact with hot gases flowing at high velocity. If it is allowable to force a coolant through a porous body, and to dilute the hot gases with this coolant, the method of "transpiration cooling" may be employed. Due to the fact that the transpired coolant oozes through the pores at low velocity, the hot gases are insulated from the porous plate, and consequently the heat-transfer coefficient from hot gas to plate is greatly reduced. Table 3 (*50*) shows this effect. When employing transpiration cooling, the plate may be held at the desired temperature by transpiration of nitrogen gas or water through the pores of the plate, producing a reduction of 73-76% in both coefficient of heat transfer from hot gases to the plate and the rate of heat transfer.

9. *Instrumentation.* In measuring individual coefficients of heat transfer, it is customary to attach thermocouples to surfaces. The leads of the thermocouple usually pass through a fluid which is warmer or cooler than the surface. Owing to heat transfer between the fluid and the leads, heat is conducted to or from the junction, and consequently the surface temperature is not the same as it would have been without using the thermocouple. The resultant error, and estimates of the correction, are given (*6, 17*). Frequently it is necessary to measure temperature of a gas by means of a thermocouple, but since the surrounding walls are at a temperature different from the gas, there is radiation error. This problem is discussed (*76, 89*).

TABLE 3—TRANSPIRATION COOLING (*50*)

Air at 692° F. Flows Over Plate at a Velocity of 600 ft./sec.

Plate	Temperature Top of Plate °F.	Transpiration Fluid	Transpiration Rate lb./hr.	Supplemental Cooling lb. H_2O/hr.	h_c Air to Plate
Solid	190	None	None	14.2	69.7
Porous	190	N_2 gas	14.5	0	18.5
Porous	189	H_2O, liquid	2.02	0	17.6
Porous	215	H_2O, liquid*	0.057	0	16.6

* Water leaves plate as vapor.

Heat Transfer with Change in Phase

1. *Boiling of Saturated Liquid.* Upon inspecting the equation $q = h_{nc}A(t_w - t)$, one would conclude that the density of heat flux (q/A) would be directly proportional to the temperature potential $t_w - t$, called Δt. Figure 8 shows a graph (*1, 65, 83, 61*) of q/A vs. Δt for heat transfer from an electrically heated platinum wire to a pool of water boiling at 1 atm. In the range AB, the liquid water is being superheated by natural convection and evaporation occurs only at the surface of the pool. As would be expected from the mechanism, q/A is proportional to $\Delta t^{5/4}$. In the range BC, bubbles form at active nuclei on the heat-transfer surface, and rise through the pool, setting up natural circulation currents. In this range of nucleate boiling, q/A varies as Δt^n, where n ranges from 3 to 4. At point C the density of heat flux goes through a maximum. In the range CD, where part of the surface is insulated with a vapor film, q/A decreases as Δt increases. At point D, the density of heat flux goes through a minimum at the Leidenfrost point (*55*). In the film-boiling region, EF, heat is transferred through the vapor film by conduction and radiation.

Further data are available (*1, 11, 14, 35*). A theoretical equation is available (*11, 68*) for the convection coefficient in the region of film-boiling, based on the assumptions of laminar flow of vapor, and heat transfer by conduction through the vapor film, after deducting radiation. The resultant equation is exactly like that of Nusselt (*85*) for film-type condensation, except that Nusselt neglected the vapor density ρ_v relative to that of the condensate, ρ_L. This equation for film-boiling is a fairly good approximation to various data (*11*), except for small wires, where the data run 30 to 100% above the predicted values (*11*).

Figures 9 and 10 show Edgerton high-speed photographs by Castles (*14, 68*) of water boiling at 212° F. on a

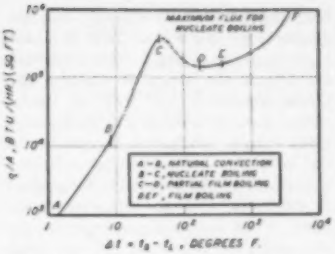
MAXIMUM FLUX FOR NUCLEATE BOILING
A-B, NATURAL CONVECTION
B-C, NUCLEATE BOILING
C-D, PARTIAL FILM BOILING
DEF, FILM BOILING
q/A, B.T.U./(HR.)(SQ. FT.)
Δt = t_s - t_l, DEGREES F.

Fig. 8. Boiling of water at 212° F. on an electrically heated platinum wire. Nukiyama *(83, 1, 65)*.

horizontal wire of Chromel C, at a density of heat flux of 72 to 80% of the peak value. In the region of nucleate boiling (Fig. 9) Δt is small, while in the region of film-boiling (Fig. 10) the wire is red hot and Δt is large.

With organic liquids, Cichelli and Bonilla *(18)* found that the peak density of heat flux occurred at a reduced pressure of one-third.

2. Boiling of Subcooled Liquid. The situation is complicated further if the temperature of the liquid is below the boiling point (Fig. 11) *(69)*. At a given instant, bubbles are present at certain parts of the surface but later condense in the nearby cold liquid *(53, 68, 69, 77)* and the phenomenon is called surface-boiling. In addition, heat is being transferred from other parts of the tube directly to cold liquid, by the mechanism of forced convection without phase change. Owing to the disturbances set up by the condensation, the heat-transfer rates are higher than without phase change. Flux densities as high as 2,000,000 B.t.u./(hr.)(sq.ft.) have been obtained with surface-boiling *(68, 69, 53)*. When the flux density is increased sufficiently the condensing step becomes the bottleneck, and the entire surface of the tube is insulated with vapor. Shortly before this condition is reached the flux density reaches a peak value *(53, 69)*.

Figure 12 *(69)* shows a logarithmic graph of the heat flux q/A plotted as ordinate vs. the total Δt from the heater to the degassed water. In the nonboiling region, the results agree with those expected from the conventional equation for forced convection without change in phase. The bulk temperature of the water was 50° F. below the boiling point. As Δt was increased surface-boiling did not start until Δt reached 88° F., indicating superheat in the liquid film.

Figure 12 shows a summary of some of the data, and it is seen that the steep portions of the curves start at various values of Δt, depending on the temperature of the water. Data for surface-boiling are plotted in Figure 13 *(69)* vs. the surface-boiling potential:

$$t_w - t_{sv}$$

where t_{sv} is the saturation temperature of the vapor. When plotted in this fashion results are insensitive to water temperature and velocity. The slope of

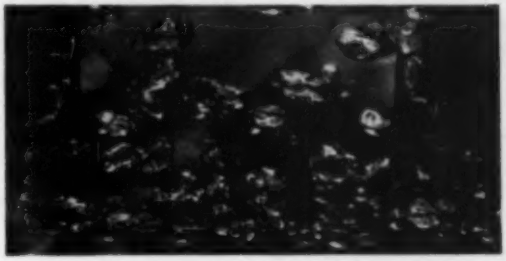

Fig. 9. Nucleate boiling of a pool of water at 212° F. by a horizontal wire of Chromel A, at a density of heat flux of 80% of the peak value, Δt is small; Edgerton photograph by Castles *(14, 68)*

Fig. 10. Film-boiling of a pool of water at 212° F. by a horizontal wire of Chromel A, at a density of heat flux of 72 % of peak value; wire is red hot and Δt is large *(14, 68)*.

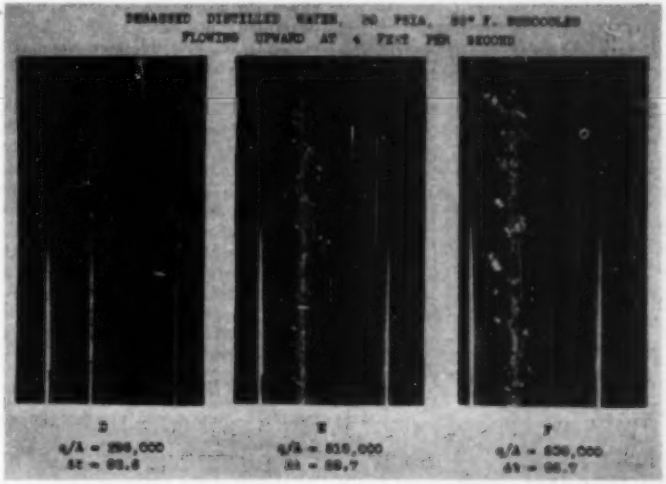

Fig. 11. Edgerton photographs of surface-boiling of subcooled degassed water flowing upward through an annulus (0.77-in. I.D.) containing a centrally located heater (0.25-in. O.D.). McAdams, Kennel, Minden, Carl, Picornell and Dew *(69)*.

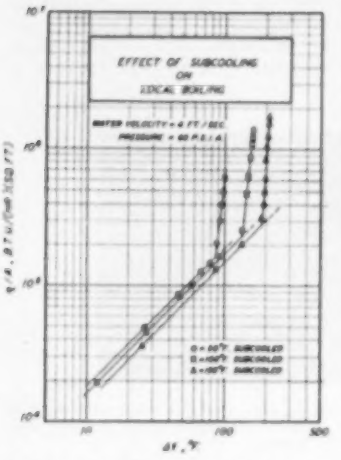

Fig. 12. Heating of degassed water flowing upward in an annulus, for 3° of subcooling. The sharp upward inflection of each curve does not start until the wall temperature is substantially above the saturation temperature, indicating superheating before surface-boiling starts *(69)*.

the curve in Figure 13 is similar to that for the boiling of a pool of saturated liquid *(1)*. Similar data are available for *n*-butyl alcohol and for aniline *(53)*.

3. Condensation of Vapors

a. Film-type Condensation of a Pure Saturated Vapor. Here it is assumed that the condensate flows past the surface in streamline motion solely under the influence of gravity, and that the latent heat of condensation is transferred through the condensation film only by conduction. The resulting Nusselt *(85)* equation is supported by experimental data for small to moderate vapor velocities; the coefficients may be larger than predicted *(63)* due to the presence of ripples. With long vertical tubes turbulence ensues and reduces the thickness of the laminar sublayer through which heat is conducted, consequently the Nusselt theory is far too conservative *(52, 20)*.

With downward flow of condensing vapor at high velocity inside tubes, the measured heat-transfer coefficients are as much as ten times *(22, 97)* those predicted conventionally.

b. Dropwise Condensation. When pure steam condenses on a clean metal, film-type condensation ensues. But if a suitable promoter is added, the metal is rendered nonwettable to the condensate *(25, 30, 36, 78, 92, 94)*, and the over-all coefficients of heat transfer from steam to water with dropwise condensation may be twenty times those with film-type condensation.

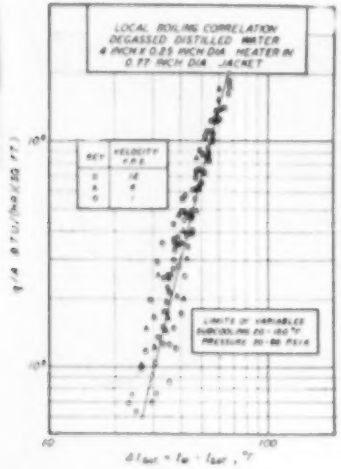

Fig. 13. Correlation of data for surface-boiling of subcooled water flowing upward in an annulus *(69)*.

Need for Further Work

In the field of conventional heat transfer, unsolved problems remain. For example, in the condensation of a vapor from a noncondensable gas, data are available only for steam and air at atmospheric pressure; no data are available for dehumidifying a mixture of various vapors and noncondensable gases. Promoters have been found to render certain metals nonwettable to condensed steam, thereby producing dropwise condensation which gives much higher coefficients of heat transfer than does film-type condensation. Pure organic vapors produce condensates which wet the tubes of the condenser, and because of the low thermal conductivities of the condensates, give much lower heat-transfer coefficients than film-type condensation of steam. Perhaps it would be possible to produce dropwise condensation. A thorough study of heat transfer and pressure drop in natural circulation vertical-tube evaporators is needed.

Novel applications of heat transfer between surfaces and fluids involve both conventional and unconventional heat-transfer fluids, frequently with unusually high density of heat flux and high temperature level. Such conditions are beyond the range of existing empirical equations, and lack of fundamental data on velocity and temperature fields causes substantial uncertainty in the reliability of theoretical relations. Consequently much remains to be done in collecting data for the new conditions. Even the physical properties are not available for many of the heat-transfer media. Further work is needed for forced convection at very high gas velocities. Table 4 summarizes needs for further work on convection.

TABLE 4.—NEEDS FOR FURTHER WORK ON CONVECTION

Molten metals and fused salts
Fluidized solids, packed beds
Flow across baffled tube banks
Natural circulation evaporators
Boiling of subcooled liquids
Condensation of vapors at high velocity
Dropwise condensation with organic vapors
Dehumidification of mixed vapors

Acknowledgment

The author desires to acknowledge helpful suggestions from a number of colleagues and fellow-workers in the field of heat transmission.

Notation

A = area of heat-transfer surface, sq.ft.

C = factor in Eq. (21) dimensionless

c_p = specific heat at constant pressure, B.t.u./(lb.)(° F.)

D = inside diameter, ft.

D_e = equivalent diameter of annulus, $D_2 - D_1$, ft.

d = prefix, indicating derivate, dimensionless

F, F' = geometrical factors for radiation between black surfaces in transparent media, dimensionless; F for direct radiation; F' for direct plus indirect

$\mathcal{F}$ = factor for total radiation between grey surfaces in transparent media, defined by Eq. (6) and (6a)

f = friction factor, $2g_c\tau_w/\rho l'^2$, dimensionless

G = mass velocity ($= w/S$), lb./(hr.)(sq.ft.)

g = local coefficient due to gravity, approximately 4.17×10^8 ft./(hr.)(hr.)

g_c = conversion factor, 4.17×10^8 lb. matter (ft.)/(hr.)(hr.)

h = local coefficient of heat transfer, conventional, $dq/(dA)(t_w - t)$, B.t.u./(hr.)(sq. ft.)(° F.)

h_a = mean coefficient of heat transfer, based on arithmetic mean temperature difference

h_e = mean effective coefficient of heat transfer, based on et-

fective temperature difference:

$$h_c = q/(A)(t_w - t_{aw})_m$$

h_m = mean coefficient of heat transfer, conventional:

$$h_m = \frac{1}{A}\int_0^A h\,dA$$

$$= q/(A)(t_w - t)_m$$

h_s = mean stagnation coefficient of heat transfer:

$$h_s = q/(A)(t_w - t_s)_m$$

h_x = coefficient of heat transfer at high L/D

h_{x1} = local coefficient of heat transfer based on initial Δt:

$$h_{x1} = dq/(dA)(t_w - t_x)$$

h_{m1} = mean coefficient of heat transfer based on initial Δt:

$$h_{m1} = \frac{q}{A(t_w - t_x)}$$

J = mechanical equivalent of heat, 778 (ft.)(lb. force)/B.t.u.

j = heat-transfer number, $(h/c_pG)(c_p\mu/k)^{2/3}$, dimensionless

k = thermal conductivity, B.t.u./(hr.)(sq.ft.)(° F./ft.)

L = length, ft.

N_t = recovery factor, defined by Eq. (13), dimensionless

q = rate of heat transfer, B.t.u./hr.
- q_c by conduction and convection
- q_k by conduction
- q_r by radiation

r, r_0 = radius (local, total), ft.

S = cross section, sq.ft.

T = absolute temperature, ° F. abs.

t = bulk temperature, ° F.
- t_a at axis
- t_{aw} of adiabatic wall
- t_s of stagnation
- t_{sv} of saturated vapor
- t_w of wall
- t_x at great distance from the plate

U = over-all coefficient of heat transfer from warmer to colder fluid, B.t.u./(hr.)(sq. ft.)(° F.)

u = local velocity, ft./hr.

V = average velocity, ft./hr.

V_x = at great distance from the plate, ft./hr.

w = weight rate of flow, lb./(hr.)(tube)

x = distance, ft.

y = distance, ft.

GREEK:

α_e = eddy thermal diffusivity, sq. ft./hr.

α_M = molecular thermal diffusivity, sq.ft./hr.

Δt = temperature difference causing flow of heat, ° F.

ϵ = emissivity, dimensionless

λ = enthalpy change upon condensation, B.t.u./lb.

μ = viscosity, lb./(hr.)(ft.) = $\mu_F g_c$, where μ_F is in lb. force (hr.)(sq.ft.)

μ/ρ = molecular diffusivity of momentum, sq.ft./hr.

$k/\rho c$ = molecular diffusivity of heat, sq.ft./hr.

ρ = density, lb./cu.ft.
- ρ_x at great distance from the plate

σ = Stefan-Boltzmann constant, 1.73×10^{-9} B.t.u./(hr.)(sq.ft.)(° F. abs.)^4

τ_w = shear stress at the wall, lb. force/sq.ft.

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(Reprints of this article will be available.)

EDITOR'S NOTE

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EVAPORATION OF LIQUIDS INTO TURBULENT GAS STREAMS

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New data are presented on the evaporation of liquids into turbulent gas streams. Tests were made using wetted plane surfaces, cylinders, spheres, and discs. Water was evaporated into air from each of the several shapes; water into carbon dioxide and into helium from cylinders; benzene and carbon tetrachloride into air from cylinders; and benzene into air from spheres. Values of j_D obtained are expressed graphically as functions of the appropriate Reynolds numbers, and are shown to agree remarkably well with data from the literature on mass transfer, heat transfer and friction.

PROBLEMS of mass transfer, heat transfer, and fluid flow are basic to the design of much of the equipment of the process industries. Knowledge of these three fields has been built up over the years largely on the basis of experimental studies of heat transfer with different fluids flowing in tubes and past various solid shapes, mass transfer or gas absorption in many types of equipment, and of friction or drag of standard shapes in moving gases and liquids. In recent years, however, it has become increasingly clear that the three processes are intimately related and that a complete understanding of turbulence and of flow conditions near phase boundaries may be expected ultimately to provide a sound basis for the development of a theory of interphase transfer as a single subject, whether it be heat, material, or momentum that is transferred. As a contribution to the development of such an understanding, this and a subsequent paper present new data on evaporation of liquids from flat surfaces, cylinders, and spheres into turbulent streams of several gases, and the effect of both scale and intensity of turbulence on the rate of mass transfer.

Traditionally, data on mass transfer have been expressed in terms of a transfer coefficient K_G, g.moles/(sec.)(sq. cm.)(atm.), or K_c, g.moles/(hr.)(sq. cm.)(g.mole/cu.cm.), where $K_c = K_G RT$. Correlations of such data have generally taken the form of empirical expressions relating the three dimensionless groups $K_c D/D_v$, Re, and Sc, where Re is the Reynolds number based on some appropriate dimension, and Sc is the Schmidt group $\mu/\rho D_v$. Thus Gilliland and Sherwood (*4*) found for vaporization of liquids into air in a wetted-wall column

$$\frac{K_c D}{D_v} = 0.023\, Re^{0.83} Sc^{0.44} \qquad (1)$$

Various attempts have been made to develop theoretical expressions for mass transfer in turbulent flow (*18*). These have resulted in the common form

$$\frac{K_c p_{BM} \phi_D}{U_c P} = \frac{f}{2} \qquad (2)$$

where ϕ_D is some function of f, Re, and Sc. Chilton and Colburn (*1*) suggest that ϕ_D may be replaced by the empirical function $Sc^{2/3}$, and that data be correlated in terms of the dimensionless group j_D, where

$$j_D = \frac{K_c p_{BM} Sc^{2/3}}{U_c P} = f(Re) \qquad (3)$$

This has worked well in many instances, and will be employed in treating the data here reported.

Theoretical equations referred to later are all based on the concept that mass transfer in a turbulent stream is proportional to the mean deviating velocity v' in the direction of transfer, and to some characteristic length related to the size of the eddies. These two quantities in turn are connected with the velocity and velocity gradient, and hence to the shear stress at the wall, and to f. Agreement between data and theory is remarkable for turbulent flow in pipes where the relation between velocity gradient and friction is known, and Equation (2) has been shown to be approximately correct for transverse cylinders, providing f represents only that portion of total drag due to skin friction. No theory exists for bluff objects where flow separation occurs, and for these cases it is convenient to plot the experimental data as suggested by Equation (3).

It may be noted that Equation (1) corresponds to $\phi_D = Sc^{0.56}$, whereas the exponent in Equation (3) is $\frac{2}{3}$. The former was obtained from experimental data, and may be presumed more reliable than the latter, which was obtained by analogy to the corresponding function for heat transfer. However, the experimental range of Sc is from 0.60 to about 2.4, which is too narrow to differentiate conclusively between the exponents 0.56 and $\frac{2}{3}$.

Experimental Procedure

The general technique employed involved the measurement of the rate of evaporation of a liquid supplied continuously to a porous surface placed in a turbulent gas stream. Data on evaporation from flat surfaces were obtained in a duct 15.2 × 61.0 cm. in cross section; evaporation from spheres, cylinders, and small discs was studied in a long round duct 10.2 cm. I.D.

Flat Surfaces. The duct used was that previously described by Sherwood and Comings (*19*). The horizontal wet test surfaces were placed in a rectangular passage 15.2 cm. wide by 61.0 cm. high, at the horizontal mid-plane and 100 cm. downstream from a reducing section preceded by about 300 cm. of 45.6 × 61.0 cm. duct. Air at controlled temperature passed over the test surface at velocities from 500 to 100 cm./sec. Air temperatures were maintained between 40 and 60° C.

[*] This is the first of two related articles by Maisel and Sherwood. The second one titled, "The Effect of Air Turbulence on Rate of Evaporation of Water," will be published in the April issue of *Chemical Engineering Progress*.

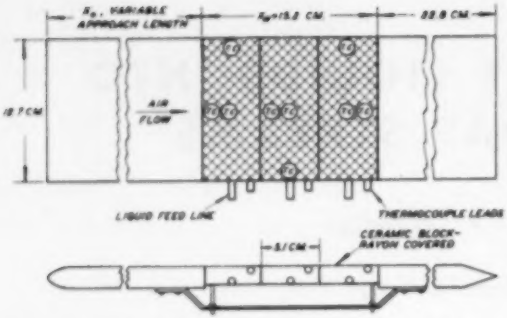

Fig. 1. Apparatus used in measuring rate of vaporization of water from flat surfaces.

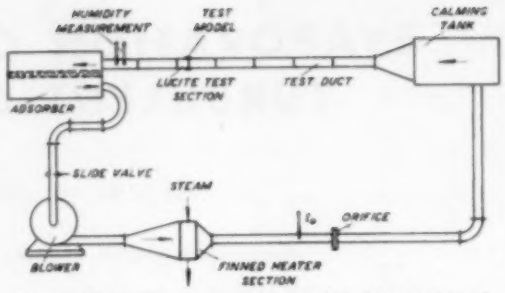

Fig. 2. Diagrammatic sketch of closed-circuit gas channel used with small cylinders, spheres, and discs.

The wet test surface consisted of one, two, or three blocks of firebrick (Johns-Manville No. 1620) cut to fit three galvanized iron pans 5.1 × 12.7 × 1.90 cm. deep. Top surfaces of the three blocks were covered by a single layer of fine-weave rayon cloth, and thermocouples placed beneath the cloth at the positions shown in Figure 1 in which the wet surfaces are shown cross-hatched. Wooden approach sections were fitted to the leading edge of the pans, as shown. These were in lengths of 13.0, 26.1, 52.1, and 102.2 cm. Water was fed to the pans through copper tubing from a supply system consisting of an inclined tube in which the meniscus was brought to a mark for readings by adding water from a 50 cc. buret. In this connection, it was found necessary to equalize total pressures in the air duct and over the inclined supply tube. Separate supply systems of this type were operated for each pan. Data were obtained only on water and air.

Temperature variations over the surface were of the order of 2-3° C. at most. The driving force used in calculating j_D was obtained by subtracting the partial pressure of water in the air stream, obtained from wet- and dry-bulb readings, from the vapor pressure of water at the mean of the several thermocouple temperatures. Because of heat inflow from the bottom and edges as well as by radiation, the surface temperature was 2-5° C. higher than the wet-bulb temperature. Air viscosity and density used in the calculations were taken at the air temperature.

Cylinders, Spheres, and Discs. Evaporation studies with these shapes were carried out in a 10.2 cm. I.D. round duct arranged so that the gas could be recirculated in a closed system, as shown diagrammatically in Figure 2. The duct proper was made up of eight sections of seamless steel tubing each 61 cm. long, fitted together by means of closely machined butt joints. The test object was mounted in a similar section made of transparent Lucite, machined to fit the steel sections and provide a continuous smooth internal duct surface. Preceding the test section was a large surge tank and converging cone 290 cm. or approximately 29 duct diameters upstream from the test section.

The gas leaving the test section passed through an adsorber, consisting of a drum carrying a perforated tray filled with granules of activated carbon or dry silica gel. The 4*R* Marvel blower operated at 3300 rev./min. by a 5-hp. motor provided 10,000 l./min. of air at 23-cm. water head. Temperature was controlled by adjusting the steam supply to the finned heater section, installed in a special adapter equipped with a by-pass line. The main velocity control was a 10-cm. slide valve installed between the adsorber and the blower. Three sizes of orifices were used, depending on the gas rate. These were calibrated in place by means of a large gasometer.

In addition to the test object, the transparent test section was fitted with a movable thermocouple to indicate gas temperature, and a 1.9 mm. *R-362-PS* Revere Pitot tube for accurate velocity traverses. Downstream from the test section were located wet- and dry-bulb thermometers for humidity determinations in runs with water.

Tests were run with water evaporating into air, helium, and carbon dioxide, and with carbon tetrachloride and benzene evaporating into air. When air was used the system was open and the air was not recirculated. With carbon dioxide and helium the system was closed and the gas recirculated, with the adsorber in operation. Special pains were taken to make the system tight and carbon dioxide or helium was introduced by displacing the air. The carbon dioxide contained 2 to 36% air, and the helium 2 to 12% air, as found by Orsat analyses for oxygen.

Cylinders. Cylinders used were of fused silica (Filtros) and were placed vertically in the center of the test section. Three thermocouples were tied to the surface of the cylinder along a vertical line, and the whole covered with filter paper held with cotton thread to provide a smooth outer surface. The cylinder was mounted in two cylindrical metal adapters machined to fit the ends of the cylinder. The diameter of the adapters was 0.8 mm. greater than that of the cylinder. The bottom section served as a liquid reservoir as well as a support. Each adapter was held in place by packing glands in holes in the Lucite test section. Liquid was fed through the lower adapter from an inclined measuring tube similar to that described for use with the flat plates. The upper adapter served as a cap and as an outlet for the thermocouple wires. The cylinder could be rotated while the run was in progress, and the three thermocouple readings were recorded with the thermocouples at the front, back, and side positions. The reported surface temperature was the average of these twelve readings, which normally differed by less than 2° C. (With the shorter of the two cylinder lengths employed, only two thermocouples were attached and eight readings obtained.)

Spheres. Spheres used were made by binding sand with precipitated calcium silicate, using a spherical mold and taking pains to remove all traces of the calcium chloride precipitating agent. Three 36-gage copper-constantan calibrated thermocouples were tied to the surface and the whole covered with absorbent cellulose tissue. A fourth thermocouple was located in the center of the sphere. The liquid was supplied through a hypodermic tube which also

served as a support at the top. A cotton wick was embedded in the bottom of the sphere, hanging down into the open end of a 8 mm. vertical glass tube immediately below the sphere. This tube extended through a packing gland at the bottom of the Lucite duct, and was connected to the inclined glass feed control tube. Liquid was fed from a buret through the hypodermic feed tube to the top of the sphere, at such a rate as to maintain a constant level in the two arms of the glass reservoir tube at the bottom. The level was maintained just below the sphere, so that the wick was kept wet. As in the case of the cylinders, the spheres could be rotated, and the maximum spread of temperatures noted was less than 2° C.

Discs. Two sizes of thin microporous ceramic discs were employed, 2.5 cm. and 3.7 cm. diameter, and 1.6 mm. thick. Four thermocouples were attached to one face covered with filter paper. This face was exposed up-wind; with the disc placed parallel to the air stream no filter paper was used. The liquid feed was from above, as in the case of the spheres. The disc rested in a shallow slot in a Lucite block forming a lower reservoir; this was connected to an external inclined glass tube in which the liquid level was held constant.

Results with Flat Surfaces

Data on evaporation of water from flat surfaces were obtained with wetted lengths (x_w) of 5.1, 10.2, and 15.3 cm., approach lengths (x_o) of 13.0, 26.1, 52.1, and 103.0 cm., and Reynolds numbers (based on total length x_t) from 65,000 to 674,000. Approximately one-third of the experimental points are given in Table 1, and shown in Figure 3 as j_D vs. $(Re)_x$, together with other data from several sources. The lower section of the solid line represents $f/2$ for smooth plates as given by Goldstein (*5*) for turbulent flow, and coincides with the line given by McAdams (*12*) for heat transfer to flat plates. The upper section (to the left) represents the theoretical equation of Blasius for $f/2$ in the streamline region.

Data from the literature were obtained without approach sections, or with x_o small compared with x_t. In the present case x_o is large compared with x_w; with the 5.1 cm. wetted section and 103 cm. approach section j_D is essentially a point value and not an average over a wetted length x_t. The new data fall well above the best line through the other points, and are badly scattered. It is evident that x_o and x_w are important, and that a good correlation cannot be obtained on the basis of x_t alone, except where no approach section is employed.

TABLE 1. EVAPORATION OF WATER FROM FLAT SURFACES

Run	x_t, cm.	N_G, gm./sq. cm./sec.	$j_D \times 10^3$	Re_x
	Length of approach section x_o = 13.0 cm.			
82	18.1	5.01	5.69	65,000
	23.2	4.18	4.68	80,000
	28.3	3.98	4.45	102,000
84	18.1	5.10	5.71	65,000
	23.2	4.27	4.78	80,000
	28.3	4.04	4.52	102,000
87	18.1	6.56	5.48	90,200
	23.2	5.66	4.69	108,000
	28.3	5.35	4.48	141,000
90	18.1	7.84	5.52	108,000
	23.2	6.15	4.64	122,000
	28.3	5.66	4.26	156,000
	Length of approach section x_o = 26.1 cm.			
27	31.2	5.78	5.06	150,000
	36.3	5.07	4.44	175,000
	41.4	4.81	4.21	194,000
28	31.2	5.60	4.90	149,000
	36.3	5.15	4.50	174,000
	41.4	4.84	4.24	198,000
30	31.2	4.85	5.21	112,000
	36.3	4.77	4.51	130,000
	41.4	4.59	4.29	140,000
32	31.2	4.50	5.82	109,500
	36.3	4.07	5.27	127,500
	41.4	3.65	4.72	145,500
37	31.2	4.38	5.79	101,000
	36.3	3.72	4.93	118,000
	41.4	3.68	4.91	134,200
	Length of approach section x_o = 52.1 cm.			
17	57.2	5.82	5.29	246,000
	62.4	4.44	4.40	255,000
	67.5	4.18	4.14	278,000
18	57.2	5.19	5.15	246,000
	62.4	4.87	4.58	255,000
	67.5	4.18	4.10	278,000
21	57.2	4.51	5.55	196,000
	62.4	3.97	4.89	218,000
	67.5	3.60	4.44	231,000
72	57.2	4.76	5.25	210,000
	62.4	3.97	4.61	220,000
	67.5	3.71	4.11	249,000
75	57.2	5.02	5.25	261,000
	62.4	5.15	4.94	286,000
	67.5	4.95	4.56	309,000
78	57.2	6.16	4.92	291,000
	62.4	5.20	4.28	316,000
	67.5	5.04	4.02	348,000
	Length of approach section x_o = 103 cm.			
58	107.1	5.96	4.81	616,000
	112.1	5.21	3.76	642,000
	117.2	4.91	3.55	675,000
59	107.1	6.16	4.45	615,000
	112.1	5.40	3.90	642,000
	117.2	5.04	3.64	674,000
62	107.1	4.89	4.76	410,000
	112.1	3.79	4.11	426,000
	117.2	3.58	3.88	447,000
65	107.1	4.54	5.12	400,000
	112.1	3.99	4.38	416,000
	117.2	3.58	4.15	433,000
67	107.1	5.62	4.74	545,000
	112.1	5.02	4.28	567,000
	117.2	4.75	4.01	596,000

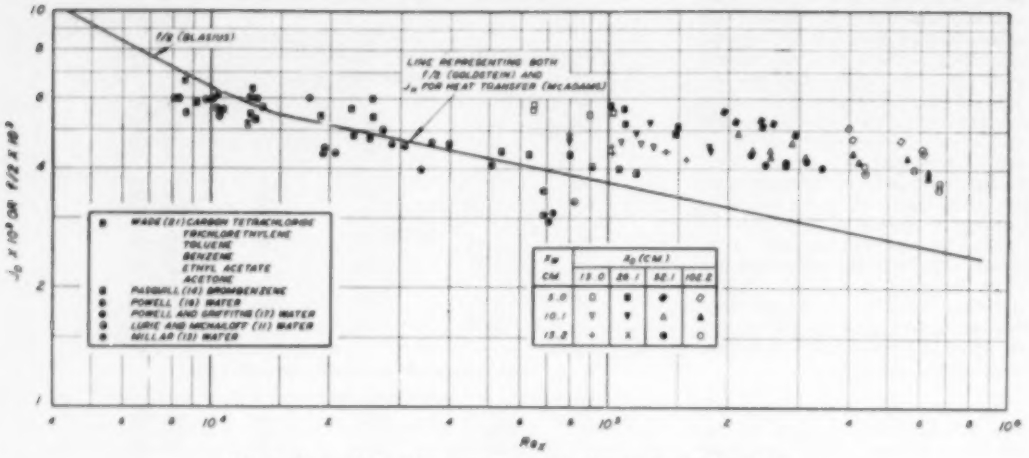

Fig. 3. Comparison of data on evaporation of water from flat surfaces.

This result might have been predicted from a consideration of the nature of flow near the leading edge of a flat plate. Starting at the leading edge the boundary layer is wholly laminar, its thickness increasing with distance downstream until it breaks more or less suddenly to form a turbulent boundary layer with a laminar sublayer. The critical distance (x) at which this change occurs corresponds to a critical value of $\frac{xU\rho}{\mu}$ of several hundred thousand. Consequently the flow conditions in the layer determining the rate of mass transfer will depend on the location of the wet section, whether in the region where the boundary layer is laminar or turbulent, or overlapping both regions. It might have been anticipated, therefore, that j_D would depend on both x_o and x_t, as well as $(Re)_x$.

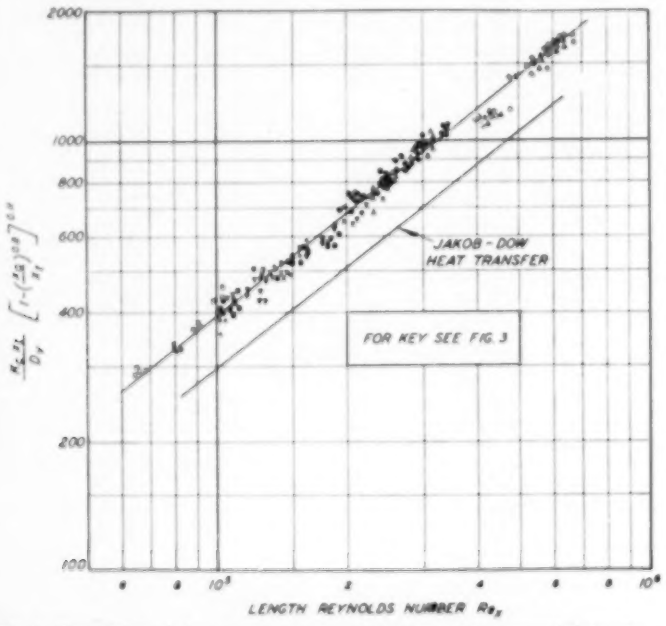

Fig 4. Correlation of data on evaporation from flat surfaces preceded by dry approach section.

For the laminar boundary layer Pohlhausen (*15*) has developed a theoretical relation for heat transfer which may be re-derived for mass transfer. The result is

$$j_D = 0.323\ Re_x^{-1/2}\left[1-\left(\frac{x_o}{x_t}\right)^{0.75}\right]^{-1/3} \quad (4)$$

This is based on a momentum balance in the boundary layer and the representation of both velocity and concentration gradients by cubic equations. Equation (4) represents point values and not the integrated average value of j_D from $x = 0$ to $x = x_t$. (Pohlhausen assumed different velocity and temperature profiles and obtained the constant 0.332 instead of 0.323).

Equation (4) cannot be expected to apply if the boundary layer is turbulent, but it suggests the basis for an empirical correlation. The same reasoning was followed by Jacob and Dow (*7*), who correlated their data on heat transfer to a cylinder placed parallel to an air stream by the equation

$$\frac{hx_t}{k} = 0.0280\ Re_x^{0.8}\left[1+0.4\left(\frac{x_o}{x_t}\right)^{2.75}\right] \quad (5)$$

Their function of x_o and x_t was tried with the present data, but a somewhat better correlation was obtained with the empirical form

$$\frac{K_c x_t}{D_v} = 0.035\ Re_x^{0.8}\frac{P}{P_{BM}}\left[1-\left(\frac{x_o}{x_t}\right)^{0.8}\right]^{-0.11} \quad (6)$$

TABLE 2. DATA ON CYLINDERS

Run	Evap. Rate g./sec. x 10^3	t_s (°C)	U_o cm./sec.	$1.27Re_o$	j_D x 10^3
Water-Air; diameter = 1.25 cm.; Length = 4.65 cm.; Wetted Surface = 19.7 sq. cm.					
22	2.22	20.6	848	8,500	12.1
23	1.84	19.0	280	3,680	17.1
24	1.18	17.9	170	1,740	16.0
25	1.85	18.6	209	2,160	14.2
26	1.75	20.8	808	1,770	11.7
27	0.86	17.0	108	1,090	20.6
29	2.05	22.2	785	7,750	8.7
30	2.91	21.9	690	6,750	9.1
31	2.51	22.1	573	5,620	9.6
32	2.19	22.1	427	4,300	10.8
33	2.91	22.5	730	7,090	7.6
34	5.55	28.5	1,640	16,000	6.6
35	5.05	28.7	1,640	16,000	5.8
37	4.55	28.3	1,360	12,200	6.4
38	3.92	28.4	1,090	10,400	6.9
39	3.24	28.4	790	7,700	7.7
40	2.04	21.6	670	6,750	8.7
41	4.94	28.1	1,990	19,700	5.7
42	4.19	28.0	1,200	11,900	6.7
43	2.44	28.1	960	9,450	7.2
44	3.12	21.9	780	7,660	8.1
45	2.82	22.4	666	6,410	8.6
46	2.56	22.8	580	5,200	9.8
47	2.09	21.2	420	4,170	10.5
48	1.69	22.7	765	7,800	7.9
49	1.58	22.5	401	3,950	8.8
50	1.10	22.7	412	2,980	10.5
51	2.67	24.4	1,520	14,500	6.5
52	2.33	24.8	1,080	11,200	7.1
53	1.79	24.6	795	7,650	8.1
54	2.62	22.8	1,590	15,400	5.8
55	2.46	22.6	1,480	14,400	5.9

TABLE 2a. EVAPORATION FROM CYLINDERS

Run	Evap. Rate g./sec.x10^2	% Air	t_s (°C)	K_c cm/sec	U_o cm/sec	$1.27Re_o$	j_Dx 10^2
Cylinder diameter = 1.42 cm.; Length = 5.7 cm.; Wetted Surface = 25.5 sq.cm.							
Evaporation of Water into Carbon Dioxide							
C1	2.44	26.9	18.5	8.9	770	14,100	5.8
C5	2.22	18.7	15.9	7.0	653	12,800	5.8
C6	1.56	9.0	15.9	4.9	512	10,700	4.7
C7	2.24	8.6	15.2	7.7	745	15,700	5.1
C9	1.76	11.0	15.5	5.4	476	9,400	5.8
C11	0.80	8.7	14.8	2.7	159	3,420	11.5
C13	1.44	2.9	14.8	4.8	370	7,950	6.4
C15	2.42	2.0	15.4	7.9	720	15,500	5.4
C17	2.56	1.7	15.9	7.4	980	20,800	3.8
Evaporation of Water into Helium							
H1	2.12	4.2	11.0	12.9	1,080	7,020	11.8
H2	2.97	1.9	11.8	12.2	910	1,600	13.6
H5	2.81	6.2	11.8	11.4	665	1,450	15.2
H7	1.88	12.5	11.8	7.7	320	920	17.9
H9	2.60	8.1	11.2	10.7	525	1,250	17.5
H11	2.85	4.7	11.5	15.8	825	1,700	17.2
H12	2.16	4.8	11.4	12.7	770	1,550	15.1

TABLE 2 b. EVAPORATION OF WATER FROM CYLINDERS

Run	Evap.Rate g./sec. x 10^3	t_s (°C)	U_o cm/sec	$1.27Re_o$	j_D x 10^3
Cylinder diameter = 1.25 cm.; Length = 3.4 cm.; Wetted Surface = 14.4 sq. cm.					
85	6.15	5.0	854	4,000	9.8
87	10.00	4.8	828	9,200	6.5
89	9.05	4.7	576	6,450	7.7
92	10.92	4.7	741	8,200	8.0
94	12.40	5.8	850	9,000	7.7
96	6.71	2.2	442	5,050	9.4
98	8.01	3.2	567	6,400	8.4
100	8.45	3.0	655	7,400	7.9
102	9.81	3.3	785	8,900	7.4
104	2.56	2.9	128	1,450	16.0
106	4.45	3.9	198	2,220	11.5
108	5.62	6.4	258	2,900	11.0
110	6.80	6.7	324	3,600	9.7
112	3.11	7.0	180	2,020	12.0
114	8.12	5.1	595	6,640	7.8
116	12.01	4.9	1,080	12,000	5.8

TABLE 2 c. EVAPORATION OF CARBON TETRACHLORIDE FROM CYLINDERS

Run	Evap.Rate g./sec. x 10^3	t_s (°C)	U_o cm/sec	$1.27Re_o$	j_D x 10^3
Cylinder Diameter = 1.25 cm.; Length = 3.4 cm.; Wetted Surface = 14.4 sq.cm.					
118	17.11	3.7	288	3,280	12.3
120	12.21	3.6	412	4,650	9.3
122	16.05	4.4	577	6,500	7.9
124	17.55	5.2	687	7,720	6.7
127	20.60	4.1	722	8,100	8.0
129	18.81	4.0	582	6,560	9.5
141	15.90	4.0	372	4,070	12.0
143	14.36	4.9	267	3,110	12.5
145	10.92	5.0	174	1,900	17.2

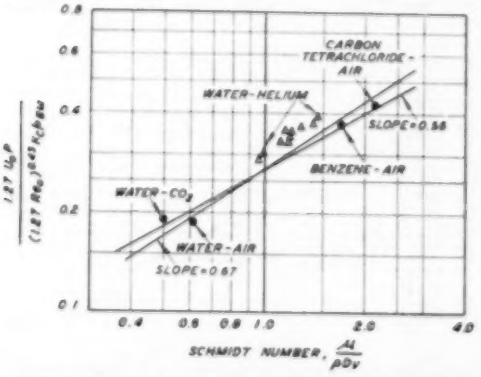

Fig. 5. Effect of Schmidt number on mass-transfer coefficients for transverse cylinders.

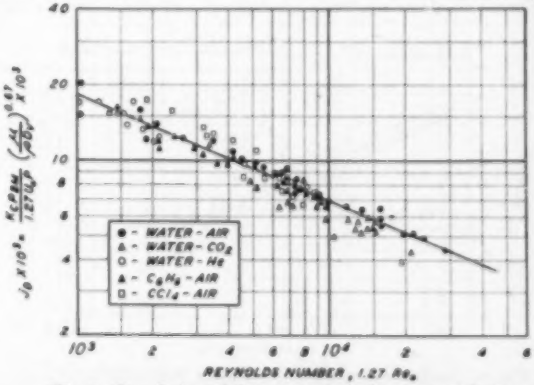

Fig. 6. Correlation of data on evaporation from cylinders using several liquid-gas systems.

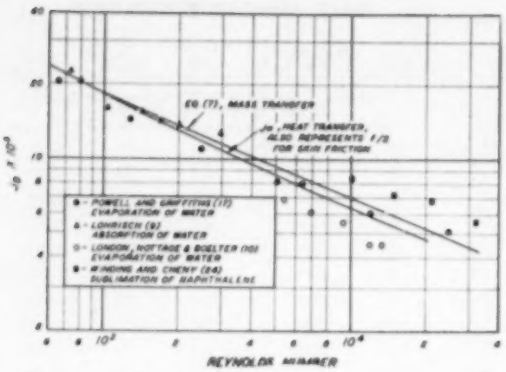

Fig. 7. Comparison of data on cylinders with data on heat transfer and skin friction.

Inserting the value of 0.60 for Sc for water in air, this becomes

$$j_D = 0.0415\ Re_o^{-0.2}\left[1 - \left(\frac{x_o}{x_t}\right)^{0.8}\right]^{-0.11} \qquad (6a)$$

The Schmidt group is omitted, since all the data were obtained with water in air, for which Sc is 0.60. Data (all tests) are plotted in this form on Figure 6, which also shows a line representing the heat-transfer data of Jacob and Dow. Data of Powell (*16*) for evaporation of water from cylinders parallel to an air stream, not shown on Figure 4, agree with the present data at low Reynolds numbers (10,000 to 30,000) and with the Jacob and Dow heat-transfer line in the vicinity of 100,000 to 300,000.

For any value of the air speed, the laminar boundary layer breaks at some more or less fixed value of x. Both x_o and x_t are necessary to fix the degree to which the wet area overlaps the critical point; $\frac{x_o}{x_t}$ alone is insufficient. It is fortuitous, therefore, that a good correlation is obtained on the basis of the product of $x_t^{-0.2}$ and a function of $\frac{x_o}{x_t}$. More data are desirable, therefore, in which both x_o and x_t are varied independently (Jacob and Dow did not vary x_t independently of x_o, since x_w was held constant).

Cylinders. Data were obtained using a 2.62 cm. O.D. cylinder in studying the evaporation of water into air. A cylinder 1.35 cm. O.D. was used for water, benzene, and carbon tetrachloride in air, and a 1.42 cm. O.D. cylinder for water in carbon dioxide and water in helium. The range of Reynolds numbers was 900 to 29,000, with gas temperatures from 20° to 60° C., and velocities from 115 to 1600 cm./sec. Data for approximately half the tests with the two smaller cylinders are summarized in Table 2.

As in the case of flat surfaces, data have been plotted as j_D vs. Re. A preliminary plot showed excellent agreement between results for 1.35 cm. cylinders 2.46 cm. long and cylinders of the same diameter 4.65 cm. long. This check indicated the end effect, due to the support and cap at the two ends of the cylinder, to be negligible with the technique employed for obtaining an average surface temperature. Values of j_D were some 10% higher for a 2.62 cm. cylinder than for one 1.35 cm. O.D. at the same Re. This is explained by the restricted air passage when the larger cylinder was used, and the greater air speed at the restricted section. Data to be discussed were all obtained with the 1.35 cm. and 1.42 cm. O.D. cylinders, for which the restriction of the air flow was very small. Careful Pitot-tube traverses at the test section showed the gas velocity to be nearly constant over the central third of the diameter, and to be 27% greater than the average velocity for the duct as a whole. For this reason the approach gas velocity is taken as 1.27 U_o in Re and j_D, where U_o and Re_o are based on the average velocity obtained from the orifice reading.

Data were first plotted on logarithmic coordinates as $\frac{K_c p_{BM}}{1.27 U_o P}$ vs. $1.27\ Re_o$ and the data for each system (water-air, water-CO_2, etc.) represented by a line having a slope of −0.43. The intercepters were then plotted as

$$\frac{1.27\ U_o P}{K_c p_{BM} (1.27\ Re_o)^{0.43}} \text{ vs. } Sc,$$

in order to verify the exponent 0.67 used on the latter group in calculating j_D. The result is Figure 5, where the four solid points represent best lines through each of the four sets of data on the first graph. In the case of water-helium, the value of Sc varied considerably with leakage of air into the helium, and the individual points are shown. It is evident that the exponent 0.67 is reasonable, although good agreement could be claimed with the exponent 0.56 found by Gilliland and Sherwood (*4*) for evaporation in a wetted-wall column.

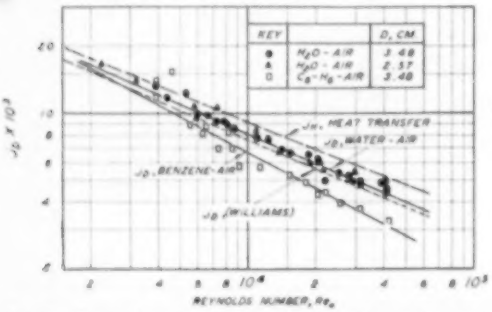

Fig. 8. Comparison of data on spheres with results for heat transfer with Williams' correlation. Abscissa is 1.27 Re_o for present data.

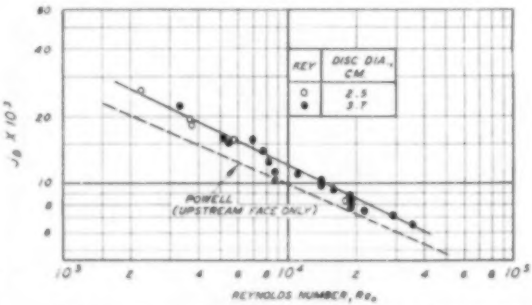

Fig. 9. Data on evaporation from two faces of discs placed at right angles to the gas stream.

The International Critical Tables value of D_v was used in calculating Sc for benzene-air, water-CO_2, and for water-air; the other values of D_v were obtained from the Gilliland (*3*) equation. For helium and carbon dioxide contaminated with air, weighted mean values of D_v, μ, and ρ were used, based on the measured concentrations of air in the two gases.

Figure 6 shows the data collected as j_D vs. Re, with a solid line of slope −0.43 best representing the points. Although it would appear that a steeper line should be drawn, the slope −0.43 is best for each system. The equation of the solid line is

$$j_D = 0.36\ Re^{-0.43} \qquad (7)$$

which is the recommended empirical equation for mass transfer to single transverse cylinders in the range Re 1,000 to 30,000 and Sc 0.5 to 2.2.

These results are compared with the data of other investigators in Figure 7, which show Equation (7) to be in good agreement with earlier data. Not only do the data on mass transfer agree with the corresponding results for heat transfer to single cylinders, but the agreement with friction data is also excellent. This is evident by the fact that the heat-transfer line shown is also an excellent representation of the skin friction data for cylinders, as obtained by Goldstein (*5*) by subtracting the form drag from the total drag.

Spheres. Data on evaporation from two sizes of single spheres are shown in Table 3 and in Figure 8, which show the points for water in air well represented by a single line, and a second line of steeper slope through the points for evaporation of benzene in air. It is not understood why the $Sc^{2/3}$ in j_D failed to bring the data for water and benzene together, in this instance, though it is conceivable that the surface of the sphere may not have been completely wet with benzene, especially at high values of Re, or that water condensed from the air in some tests.* Because of the greater driving force, greater molecular weight, and smaller liquid density, the volume rate of liquid feed was necessarily five to ten times as great for benzene as for water, and there was some evidence that the surface was not always completely wet. Water data are doubtless the more reliable.

Figure 8 also shows the line obtained by Williams (*23*) in an extensive unpublished study of the data of Powell (*16*), Froessling (*2*), Johnstone and Williams (*8*), Hatta et al (*6*), Takahasi (*20*), and Whitman et al (*22*). Most data considered by Williams were for evaporation of liquids from relatively small liquid drops, though a few were for spheres comparable in size to those used in the present work. It is evident that the new data on water in air agree well with the correlation of Williams. The upper dotted lines represents the correlation of data for heat transfer to spheres in air as recommended by McAdams (*12*). These results cannot be compared with $f/2$ for spheres, since the data on total drag have not been separated into form drag and skin friction.

Discs. Data on evaporation from both faces of the two small discs are shown in Figure 9, which again shows a correlation in terms of j_D vs. Re. Data plotted were obtained with the disc placed normal (at 90°) to the air

* Tests made with air specially dried by silica gel gave the same results.

TABLE 3. EVAPORATION FROM SPHERES

Run	Evap. Rate g./sec. x 10^2	t_g (°C)	U_o cm/sec	$1.27Re_o$	$j_D \times 10^2$
Water-Air; Diameter = 2.48 cm.; wetted surface = 28.1 sq.cm.					
S10	2.58	28.6	501	12,300	7.65
S11	4.25	25.8	765	18,500	6.48
S12	8.54	25.2	619	15,300	6.65
S13	8.14	24.6	530	12,200	6.84
S14	2.80	24.3	434	10,800	7.56
S15	2.34	28.8	342	8,600	8.47
S16	2.04	28.6	292	7,400	9.07
S17	1.56	25.9	258	6,600	9.78
S18	1.72	25.4	308	7,800	9.22
S19	1.22	24.1	210	5,900	9.80
S20	0.86	22.6	164	4,400	11.70
S21	8.62	28.0	820	20,600	6.11
S22	4.04	28.0	998	25,300	5.24
S28	8.92	21.8	1,060	27,400	5.28
S24	4.95	28.4	1,280	32,300	4.98
S25	2.54	17.2	1,390	39,200	4.77
S26	2.57	17.5	1,470	41,500	4.62
S27	6.25	22.8	1,600	40,800	4.93
S28	4.77	22.3	1,530	40,500	4.48
S29	4.45	28.5	1,280	32,000	4.79
S30	3.74	24.8	909	28,400	4.84
S31	1.32	22.9	204	5,400	12.35
S32	1.01	28.0	148	3,900	13.30
Diameter = 2.55 cm.; Wetted surface = 20.4 sq. cm.					
S33	1.11	27.2	209	5,700	9.56
S34	1.46	29.7	447	8,100	8.64
S35	1.90	30.0	610	10,800	7.46
S36	1.96	29.3	765	18,700	6.64
S37	2.60	30.3	1,220	22,200	5.58
S38	2.86	30.3	1,560	28,300	5.06
S39	3.12	27.2	1,590	29,200	5.31
S40	2.36	27.1	1,540	27,800	4.94
S41	2.94	26.0	1,210	21,600	5.92
S42	2.31	25.8	1,020	18,400	5.77
S43	1.37	28.8	316	5,800	10.27
S44	0.78	21.6	176	3,100	12.52
S45	0.56	20.0	117	2,300	16.20
Benzene-Air; Diameter = 2.48 cm.; wetted surface = 28.1 sq.cm.					
S152	9.2	6.0	225	9,200	5.59
S154	9.3	6.2	268	7,600	6.92
S155	8.9	5.8	288	6,500	8.48
S156	9.8	5.7	164	4,700	15.63
S157	7.9	6.1	127	3,900	11.42
S158	7.6	6.0	108	3,100	12.71
S159	8.5	6.0	195	5,500	8.68
S160	11.9	6.0	285	8,100	8.28
S161	9.2	5.7	217	6,400	8.08
S162	10.6	6.0	204	5,600	6.97
S162	11.5	5.9	416	11,800	5.52
S164	12.8	5.0	540	15,200	5.17
S165	15.3	5.5	626	17,900	4.89
S166	15.2	5.9	727	20,600	4.23
S167	17.3	5.5	880	25,400	4.21
S168	17.3	6.0	980	26,800	3.81
S169	20.3	5.9	1140	32,200	3.68
S170	27.3	5.9	1480	41,700	3.14

stream. Values of j_D were 3% lower with the disc at 45°, and 7% lower with the disc at 0° (parallel to the air flow). These may be compared with the results of Powell (*16*) for evaporation from the upstream face of a disc, as indicated by the dotted line. Powell found the maximum rate from the upwind face of a disc set at 40°. With the disc at 90°, Powell found the rate to be 10-15% greater from the upwind than from the downwind face.

Summary

When expressed as j_D, j_H, or $f/2$, data on mass transfer, heat transfer, and friction agree well in the range of Re from 1,000 to 30,000 for single cylinders placed normal to a turbulent gas stream. Agreement is also excellent for flat plates involving no dry or unheated approach section near the leading edge. In the case of spheres j_H and j_D agree within a few per cent for values of Re from 3,000 to 40,000; data on skin friction are not available for comparison.

Mass-transfer rates in turbulent air streams may be expressed by the following empirical relations:

Flat surfaces: $x_a = 0$:

$$j_D = 0.037\ Re_x^{-0.2};$$

for

$$Re_x 10^5 \text{ to } 3 \times 10^6 \qquad (8)$$

Flat surfaces, with approach section of length x_a:

$$j_D = 0.0415\ Re_x^{-0.2}\left[1-\left(\frac{x_a}{x_t}\right)^{0.8}\right]^{-0.11} \qquad (6a)$$

for Re_x 6×10^5 to 7×10^6, and x_a/x_t 0.45 to 0.95, and x_a 1.3 to 10.3 cm.

Single cylinders:

$$j_D = 0.36\ Re^{-0.43} \qquad (7)$$

for

$$Re\ 6 \times 10^2 \text{ to } 3 \times 10^4$$

Single spheres:

$$j_D = 0.43\ Re^{-0.44} \text{ (Williams)} \qquad (10)$$

for

$$Re\ 2 \times 10^3 \text{ to } 5 \times 10^4$$

Acknowledgment

Thanks are due Messrs. B. P. Devins, L. E. Robb, R. W. Townsend, and J. M. Glassett, who carried out portions of the experimental studies. The work was made possible by the grant of a graduate fellowship by the Proctor and Gamble Co.

Notation

C = specific heat of fluid, g.cal./(g.)(° C.)

D = diameter of cylinder, sphere, or disc, cm.

D_v = diffusion coefficient, or diffusivity, sq.cm./sec.

f = Fanning friction factor, dimensionless

h = heat-transfer coefficient, g.cal./(sec.)(sq.cm.)(° C.)

$j_D = \dfrac{K_c p_{BM}}{U_a P}(Sc)^{2/3}$ (In small test duct U_a is replaced by $1.27U_a$)

$j_H = \dfrac{h}{cU_a\rho}\left(\dfrac{c\mu}{k}\right)^{2/3}$

k = thermal conductivity, g.cal./(sec.)(sq.cm.)(° C./cm.)

K_c = mass-transfer coefficient, g. moles/(sec.) (sq. cm.) (g. mole/cu.cm.)

p_{BM} = log mean pressure of inert or nondiffusing gas, atm.

p_a = partial pressure water vapor in air, mm. Hg.

P = total pressure, atm.

Re = Reynolds number, $\dfrac{DU\rho}{\mu}$

$Re_a = \dfrac{DU_a\rho}{\mu}$

$Re_x = \dfrac{x_t U_a \rho}{\mu}$

Sc = Schmidt group, $\dfrac{\mu}{\rho D_v}$

t_s = average surface temperature, ° C.

U_a = average velocity of gas stream, cm./sec.

x = distance downstream from leading edge of plate, cm.

x_a = length of unheated or dry section of plate preceding heated or wet portion, cm.

x_t = total length $x_a + x_w$ from leading edge to downstream edge of heated or wet section of plate, cm.

x_w = length of heated or wet section of plate, cm.

μ = gas viscosity, g./(sec.)(cm.)

ϕ_D = function appearing in Equation (*2*)

ρ = gas density, g./cu.cm.

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Discussion

Anonymous: In connection with the experiments mentioned, Dr. Sherwood said that the surface temperature of the flat surfaces was from two to five degrees over the wet-bulb temperature. Was the surface thoroughly wet?

T. K. Sherwood: Of course, if you have a pan with a porous material in it and keep the upper surface completely wet, you will still get a temperature above that of the wet bulb. The entire surface of the test object was not completely wet, of course, but the vaporization surface was completely wet.

G. G. Brown (University of Michigan, Ann Arbor): Your efforts to correlate experimental data using various exponents on the Schmidt group brings to mind a paper presented at the Tulsa meeting. The author found his data in the turbulent region for packed towers could be better correlated by leaving the Schmidt number out entirely. If this is true would you expect the Schmidt number to appear with different exponents for different conditions?

T. K. Sherwood: We thought at one time that the Schmidt group was rather unimportant for gas flow in packed towers. It may be that the effect of the Schmidt group is smaller for turbulent flow over packing or bluff objects than for flow over a smooth surface parallel to the gas stream, but this is hard to determine by vaporization or absorption tests where the Schmidt group can be varied only from 0.6 to about 2.5.

(Presented at Twelfth Regional Meeting, Montreal (Que.), Canada.)

HEAT AND MASS TRANSFER IN FLUIDIZED SYSTEMS

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Rates of heat and mass transfer between the solid particles and the gas stream were measured for silica gel and activated alumina fluidized in air. Data were obtained in a vacuum-jacketed glass tube 2.3 in. in diameter. Particle-size ranges studied were 14-20, 20-28, 28-35 and 35-48 mesh, and the air mass velocity was varied from 300 to 750 lb./(hr.)(sq.ft.). Mean temperature and partial pressure differences between the fluidized solid and gas stream were evaluated from thermocouple readings taken at intervals through the height of the bed.

The results, interpreted as heat and mass transfer coefficients, h_a and k_g, were correlated by the dimensionless equations:

$$\frac{h_a d_p}{k} = 0.0135 \left(\frac{d_p G}{\mu} \right)^{1.30}$$

$$\frac{k_g p_{bm} M_a}{G} = 0.00180 \left(\frac{d_p G}{\mu} \right)^{0.30}$$

Variations in void space and particle density were insufficient to establish completely the influence of these variables although incomplete data indicate a small increase in the coefficients with an increase in particle density. The low values of h_a and k_g in comparison with the results for fixed beds, and their increase with particle size, would be expected from the fact that the particles tend to move with the gas in the fluidized condition.

ONE of the characteristics observed in reactors in which the solid, catalytic material is fluidized in the stream of reactant gases is the uniformity of temperature in the direction of gas flow. Temperature variations within the bed in the axial direction are small, even in cases where the heat of reaction is large. This is in decided contrast to the situation existing in fixed-bed reactors, where temperature differences of 100° F. between the top and bottom of the bed are not uncommon. To explain this contrast on the basis of the ability of the solid particles in the fluidized case to move rapidly from one part of the reactor to another and in this way achieve the effects of thorough mixing, it is necessary to postulate a high heat transfer rate between the catalyst particles and the gas. If this were not so, the rapid mixing of the particles would not be effective in reducing the temperature gradient within the reactor. Since the area for heat transfer per unit volume in a fluidized system is very large, because of the small particle size, the heat-transfer rate can be quite high even though the heat-transfer coefficient, between gas and solid phases, is itself low. For example, if the fluidized particles are spheres of an average diameter of 0.0029 in. (200 mesh) and the spheres in the fixed bed are 0.25 in. in diameter, the surface area per unit volume of reactor for the fluidized case would be 43 times as large as that in the fixed bed (allowing for 50% increase in porosity upon fluidization).

Results of McCune and Wilhelm (*3*) on the measurement of mass transfer coefficients in solids fluidized in liquids lend validity to the belief that it is not the high transfer coefficient, but rather the large area, that leads to high transfer rates in fluidized systems. Their results led to mass transfer coefficients for the evaporation of naphthalene balls, fluidized in water, which were lower than those for a single ball of the same diameter held in a fixed position in the stream.

The purpose of the present work was to study further the transfer rates in fluidized beds by measuring the rate of desorption of water from solid particles fluidized in a stream of air. By observing gas temperatures as a function of bed height, it was possible to determine both heat and mass transfer coefficients between the solid particles and the air stream.

Scope of Work

In order to utilize the scheme of desorption of water from the solid particles, the material must have a high capacity for water and also must not agglomerate at high moisture contents. Silica gel and activated alumina were found to satisfy these requirements and were used in all the tests.

While it would have been desirable to study particle sizes as low as 300 mesh, the bed height required for saturation of the air is too small under those conditions to measure satisfactorily the temperature gradient in the bed. Accordingly, heat and mass transfer coefficients were evaluated for four particle-size ranges, 14-20, 20-28, 28-35 and 35-48 mesh, and for air mass velocities of 250 to 750 lb./(hr.)(sq.ft.).

Experimental Work

The central feature of the apparatus, shown schematically as a whole in Figure 1, was the vacuum-jacketed glass tube in which the solids were fluidized. It was 2.3 in. in diameter (I.D.), 23 in. long, and fitted at either end with screens to hold the solid particles. The screens were attached to brass caps which contained manometer ports, and, at the bottom, openings for compressed air and for charging and discharging the solids. Inside surfaces of the jacket in the tube were silvered to reduce further heat transfer with the surroundings.

Air fed to the bottom of the fluidization tube first was thoroughly dried with silica gel and preheated electrically as shown in Figure 1. The drier was of ample size and the silica gel regenerated frequently to make sure that the air entering the bed had a negligible moisture content. The rate of evaporation of water was determined by weighing, be-

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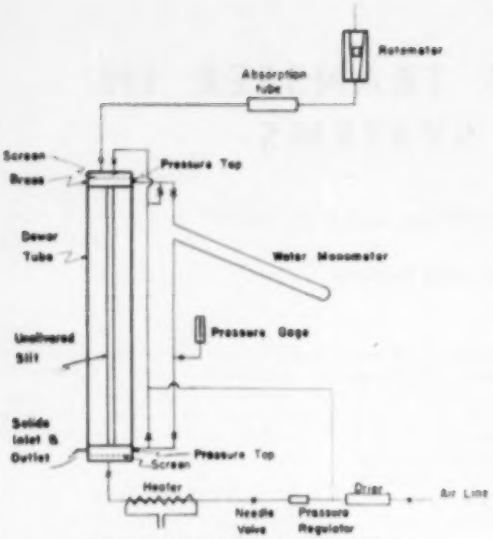

Fig. 1. Schematic Drawing of Apparatus.

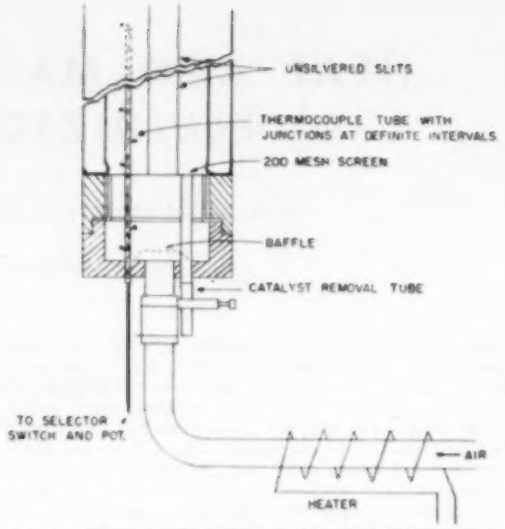

Fig. 2. Thermocouple Assembly and Lower Section of Bed.

fore and after the run, a silica gel absorber placed in the exit line from the fluidization tube. The dry air rate was measured with a rotameter placed after the absorber as shown in Figure 1.

Gas temperature at the bottom of the bed was measured with a copper-constantan thermocouple placed directly below the lower screen as illustrated in Figure 2. The temperature at any bed height was determined by a differential thermocouple with one junction at the bottom of the bed and the other at the prescribed bed depth. Thus the temperature drop of the air as it passed through the bed was the measured quantity, but the actual temperature level could be obtained from the bottom thermocouple reading. During the first part of the work a single, movable thermocouple junction was employed to determine the temperature drop at different bed heights. However, the multiple junction, fixed position assembly shown in Figure 2 was found to give more reproducible results and was substituted for the original scheme. The assembly was made as small as possible (⅛ in. wide and 1/16 in. thick) in order to reduce its effect on the flow conditions within the bed. Positions of the junctions on the assembly corresponded to bed heights of ¼, ½, ½, 1, and 2 in.

In order to avoid large changes in the moisture content of the solids, and hence a change in fluidization conditions, it was necessary for the run time to be as short as possible. This required special attention to the problem of reaching steady-state conditions before the run was started. The plan of operation finally adopted consisted of the following steps:

1. Adjusting air temperature to proper value while by-passing fluidization tube
2. Introduction of solid material at a temperature as close as possible to equilibrium temperature obtained during run
3. Passing air through bed for several minutes to allow system to approach thermal equilibrium
4. Finally, passing exit gas through absorption tube for a measured time interval, usually 3 min.

At the beginning of each test the particles were approximately saturated and the usual change in water content during a run was about 3% by weight of the dry solids.

Heat Transfer Coefficients

Method of Calculation. To evaluate the heat transfer coefficient, the temperature difference between the gas stream and the fluidized particles must be known. Gas temperatures were measured directly, but not the particle temperature. However, if there is no heat transfer with the surroundings, and the bed height is sufficient, thermal equilibrium will be obtained and the solid temperature will be equal to that of the air. Since the motion of the particles is rapid within the bed, the solid temperature should be essentially constant. If this assumption is made, a knowledge of the gas temperature at various bed heights is sufficient to evaluate the heat transfer coefficient.

The type of temperature distribution observed is illustrated in Figure 3 where experimental data for run 158M are plotted. When the dry air first meets the fluidized particles, the driving force for evaporation of water is large, and the corresponding rate of heat transfer from the air to the particles to supply the heat of evaporation is high. Accordingly, the temperature gradient of the air is rapid at first, but then decreases until at a bed depth of about 2.0 in. (in run 158) the air temperature is constant. At this point the moisture content of the air is the equilibrium value with respect to the solid particles. No further transfer of water or heat between the gas and particles occurs as the air passes on through the bed. For this particular run the solid temperature is seen from Figure 3 to be 70.4° F. In order to ensure the attainment of equilibrium, the total bed height was usually maintained at 4 in. Thicker beds were not desirable because of the increased possibility of variations in solid temperature.

The usual equation for heat transfer

$$dq = h_g(t_g - t_s)dA \qquad (1)$$

may be handled in two ways to evaluate the heat transfer coefficient, h_g. If A' represents the area of fluidized particles per unit height of bed, and q total heat transfer per unit time in the entire bed, direct integration of (1) leads to the following form

$$h_g = \frac{q}{A' \int_o^{x_e} (t_g - t_s)dx} \qquad (2)$$

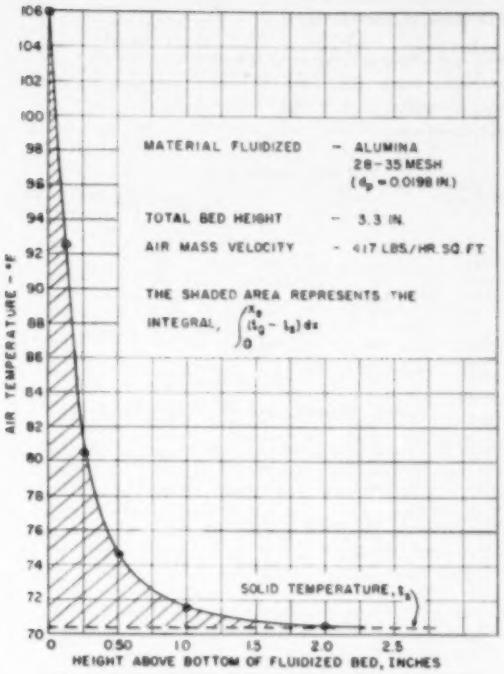
MATERIAL FLUIDIZED - ALUMINA
28-35 MESH
(d_p = 0.0198 IN.)
TOTAL BED HEIGHT - 3.3 IN.
AIR MASS VELOCITY - 417 LBS./HR. SQ. FT.
THE SHADED AREA REPRESENTS THE INTEGRAL, $\int_0^{x_2} (t_g - t_s)\,dx$
SOLID TEMPERATURE, t_s
AIR TEMPERATURE - °F
HEIGHT ABOVE BOTTOM OF FLUIDIZED BED, INCHES

Fig. 3. Air Temperature vs. Bed Height for Run 158.

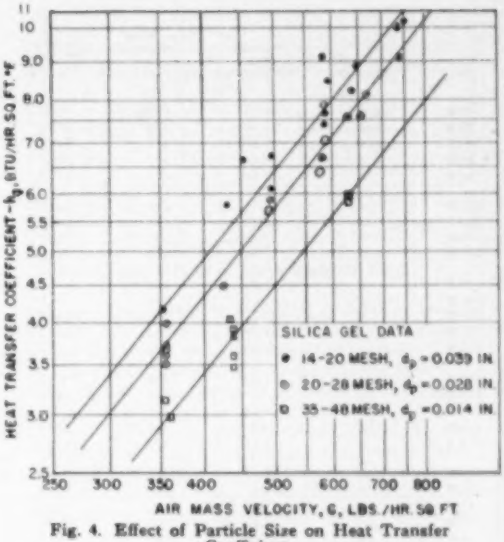
SILICA GEL DATA
14-20 MESH, d_p = 0.039 IN.
20-28 MESH, d_p = 0.028 IN.
35-48 MESH, d_p = 0.014 IN.
HEAT TRANSFER COEFFICIENT - h_g, BTU/HR. SQ. FT. °F
AIR MASS VELOCITY, G, LBS./HR. SQ. FT.

Fig. 4. Effect of Particle Size on Heat Transfer Coefficient.

The integral, and hence h_g, can be obtained by measuring the area included between the gas temperature curve and the horizontal line representing t_s on Figure 3.

Since both the silica gel and alumina particles employed were of irregular shape, the true area for heat transfer was difficult to determine. However, an apparent area, which will reflect the effect of particle size, was evaluated by assuming that the particles were spherical and of an average diameter equal to the mean of the mesh-size openings. With this procedure the effect of particle shape is not taken into account and may influence the heat transfer coefficient. As will be seen later, no discernible difference was found between the results for alumina and silica gel indicating either that particle shape is unimportant, or more probably, that the silica gel and alumina particles were not greatly different. The area per unit height, A', was computed from the mass m of dry solids and the observed total height of the fluidized bed, according to the equation,

$$A' = \frac{6m}{\rho_s d_p x_t} \qquad (3)$$

In this expression, x_t designates the total bed height and d_p the average particle diameter computed on the basis of a spherical shape as previously explained. The density of the solid material, ρ_s, was measured by water displacement of the saturated particles and found to be 1.30 g./cu.cm. for silica gel and 1.60 for alumina.

Consistency of the temperature measurements in the gas phase can be examined by writing Equation (1) in the second form,

$$h_g = \frac{1}{A'x}\int \frac{dq}{t_g - t_s} \qquad (4)$$

and noting that the logarithmic mean temperature difference is applicable. Under these conditions, for any bed height x, Equation (4) can be integrated to give

$$h_g = \frac{q_x}{A'x(t_g - t_s)_{l.m.}} \qquad (5)$$

Here q_x is the heat transfer rate up to a bed height of x, and $(t_g - t_s)_{l.m.}$ is the logarithmic mean of the temperature differences at the bottom of the bed and at the height x. The reliability of the gas temperature measurement at any value of x could be checked by comparing the coefficients computed from Equations (2) and (5). In general the agreement between these values was good. For example for run 158 (Fig. 3) h_g from Equation (2) was 4.0 B.t.u./(hr.)(sq.ft.)(° F.), while Equation (5) gave values of 4.3 at $x = 0.5$ in. and 3.9 at $x = 1.0$ in. Results from the graphical integration were used in the correlations.

Equation (2) is valid regardless of heat exchange between the fluidized bed and its surroundings, provided the heat transferred, q, is computed from the weight of water evaporated. On the other hand, Equation (5) rests upon the assumption of adiabatic operation. The approach to adiabatic conditions can be checked by determining the heat transferred, q', based upon the mass flow rate of the air, its specific heat, and its over-all temperature drop through the bed. In analyzing the data, all runs for which q and q' differed by more than 15% were discarded. The average deviation from adiabatic operation was 8%. This procedure also provided a means of discarding those runs for which steady-state thermal conditions were not achieved.

In order to calculate q, heats of desorption of water from silica gel and alumina were required. For silica gel this quantity was computed first from heat of wetting data supplied by the Davison Chemical Co. (1). Values so obtained were $1.14(\Delta H)$ at a water content (in the silica gel) of 15 wt. % and 1.05 (ΔH) at a water content of 30%, where ΔH is the heat of vaporization of water at the same temperature. These results were then checked by

TABLE 1—SUMMARY OF HEAT AND MASS TRANSFER DATA

S.G.—Silica Gel
A—Alumina

Mesh Size: 14-20, $d_p = 0.00328$ ft. (Average particle diameter)
20-28, $d_p = 0.00224$
28-35, $d_p = 0.00165$
35-48, $d_p = 0.00117$

Run No.	Fluidized Material	Particle Size (Mesh Range)	Air Mass Velocity G, lb./(hr.)(sq.ft.)	Entrance Air Temp. t_{a_1}, °F.	Solid Temperature t_s, °F.	Total Heat Transfer Rate, B.t.u./hr. q	q'	h_g B.t.u./(hr.)(sq.ft.)(°F.)	k_g lb. moles/(hr.)(sq.ft.)(atm.)
88M	A	35-48	453	103.2	64.8	121.	120.	3.3	0.49
92M	A	35-48	425	105.0	69.5	110.	105.	3.8	0.57
93M	A	35-48	425	100.0	64.5	112.	110.	3.8	0.50
98M	A	35-48	427	100.0	65.0	106.	103.	4.0	0.59
99M	A	35-48	427	107.0	73.0	112.	106.	3.9	0.58
102M	A	35-48	427	106.0	71.2	106.	103.	3.3	0.49
103M	A	35-48	427	106.3	68.6	107.	112.	3.6	0.53
110M	A	35-48	432	99.0	64.0	110.	104.	3.6	0.53
130M	A	35-48	432	94.7	63.6	101.	94.	3.9	0.58
142M	A	28-35	300	98.0	62.0	74.6	73.6	3.0	0.44
143M	A	28-35	315	104.0	67.8	81.4	79.0	3.1	0.46
148M	A	28-35	330	105.0	66.8	92.8	87.1	3.3	0.49
149M	A	28-35	330	108.2	69.7	89.5	87.6	3.4	0.50
151M	A	28-35	308	105.0	74.0	68.7	66.3	3.3	0.49
155M	A	28-35	308	97.5	68.8	65.7	62.1	3.2	0.47
157M	A	28-35	323	104.0	74.0	72.8	67.8	3.5	0.52
158M	A	28-35	617	106.0	70.5	103.	102.	4.1	0.60
160M	A	28-35	447	106.0	71.3	111.	107.	4.5	0.66
163M	A	28-35	432	103.5	72.1	87.3	93.7	3.6	0.53
164M	A	28-35	617	108.0	74.4	93.3	95.4	4.0	0.59
165M	A	28-35	432	109.5	76.5	90.2	98.5	4.0	0.59
166M	S.G.	35-48	432	102.0	80.7	61.4	63.5	4.0	0.59
167M	S.G.	35-48	432	102.6	83.6	61.3	56.8	4.1	0.60
168M	S.G.	35-48	432	101.5	83.5	58.3	53.8	3.4	0.50
169M	S.G.	35-48	432	101.5	83.5	51.3	53.8	3.6	0.54
173M	S.G.	35-48	432	92.5	75.7	49.2	50.1	3.8	0.56
175M	S.G.	35-48	432	97.0	79.0	59.1	53.7	3.9	0.58
18K	S.G.	14-20	423	107.0	70.2	124.	111.	5.8	0.86
23K	S.G.	14-20	449	97.0	72.0	86.5	77.8	6.7	0.99
25K	S.G.	14-20	582	93.0	70.6	99.0	90.5	9.1	1.34
27K	S.G.	14-20	591	97.0	74.0	102.	94.0	8.4	1.24
29K	S.G.	14-20	499	94.5	74.5	74.5	69.1	6.7	0.99
30K	S.G.	14-20	499	94.5	75.5	71.0	67.5	6.1	0.90
36K	S.G.	14-20	356	92.5	69.2	64.4	58.5	4.2	0.62
40K	S.G.	20-28	356	96.0	70.0	74.1	64.2	3.7	0.55
41K	S.G.	20-28	356	96.0	71.8	67.7	60.0	3.5	0.52
42K	S.G.	20-28	356	96.0	67.6	75.7	70.2	3.6	0.53
43K	S.G.	20-28	356	96.0	69.0	76.5	66.7	3.7	0.55
44K	S.G.	20-28	356	96.0	71.0	70.5	61.3	4.0	0.59
52K	S.G.	20-28	494	93.0	70.9	90.2	79.2	5.8	0.85
53K	S.G.	20-28	494	94.0	71.6	84.9	76.6	5.9	0.87
55K	S.G.	20-28	629	94.0	72.1	105.	96.7	7.8	1.02
58K	S.G.	20-28	432	96.0	73.2	64.2	69.6	4.5	0.67
63K	S.G.	20-28	581	98.0	73.2	112.	100.	7.1	1.05
62K	S.G.	20-28	588	98.0	74.3	109.	97.5	7.9	1.17
64K	S.G.	20-28	662	97.5	72.7	123.	114.	8.2	1.21
65K	S.G.	20-28	654	97.0	74.4	116.	106.	7.5	1.11
67K	S.G.	20-28	578	97.0	72.1	108.	101.	6.4	0.95
69K	S.G.	28-35	420	101.0	72.1	75.9	85.2	4.1	0.60
71K	S.G.	28-35	420	100.	73.3	80.5	78.9	4.1	0.60
73K	S.G.	35-48	360	99.4	70.5	80.7	73.3	3.0	0.44
74K	S.G.	35-48	353	99.7	72.9	75.5	66.4	3.2	0.47
82K	S.G.	14-20	740	98.0	74.5	133.	120.	10.0	1.48
83K	S.G.	14-20	740	98.0	74.8	132.	120.	10.0	1.48
84K	S.G.	14-20	755	98.0	71.1	151.	140.	9.1	1.34
85K	S.G.	14-20	755	98.0	74.9	131.	123.	10.2	1.51
97K	S.G.	35-48	626	93.5	69.8	108.	101.	5.9	0.87
98K	S.G.	35-48	626	94.2	71.9	103.	96.1	5.8	0.86
112K	S.G.	28-35	575	88.0	67.1	96.4	85.0	5.8	0.86
113K	S.G.	28-35	575	88.0	68.8	87.2	76.0	6.0	0.88
121K	S.G.	14-20	584	91.0	68.4	98.3	91.4	7.7	1.14
122K	S.G.	14-20	584	91.0	70.1	94.6	84.5	7.3	1.08
124K	S.G.	14-20	639	93.0	69.3	113.	105.	8.2	1.21
125K	S.G.	14-20	640	94.5	72.3	112.	99.	9.0	1.33

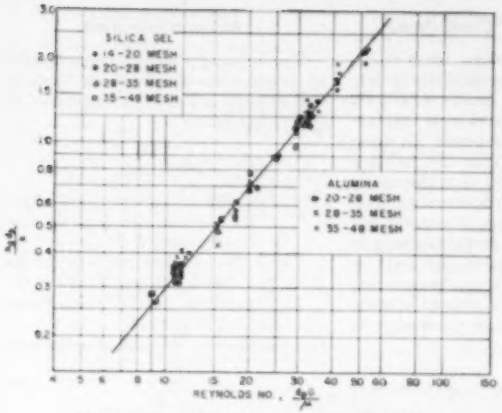

Fig. 5. Correlation of Heat Transfer Data.

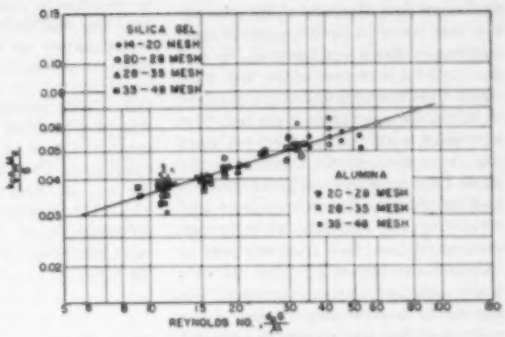

Fig. 6. Correlation of Mass Transfer Data.

measuring the slopes of the straight lines obtained by plotting the equilibrium pressure of water vapor over silica gel vs. the vapor pressure of pure water (the method of Othmer and Sawyer (*4*)). The value of these slopes, equal to the ratio of the heat of desorption to that of vaporization of pure water, was 1.15 at 15% water content and 1.08 at 30% water content. In calculating heat transfer coefficients, the heat of desorption at the average water content of each run was used. In the case of alumina, the heat of wetting, according to available data (*6*), is less than 1.0 cal./g. of water at 20° C. Therefore, the heat of desorption was assumed equal to heat of vaporization for alumina.

Consideration of Errors. The assumption of a uniform solid temperature throughout the fluidized bed may introduce some uncertainty in the results, although this is believed to be relatively small because the total bed height was held to as low a value as possible, consistent with the requirement that equilibrium be attained. The usual bed height was 4.0 in. and the maximum 6.0 in. This error would be most pronounced at low gas velocities due to the low rate of turnover of solid particles. The direction of the error is such that the transfer coefficients reported here would be less than the true values.

It does not seem likely that the thermocouple readings within the bed were influenced significantly by the solid particles. The small area and time factors with respect to contact between thermocouple and solid particles would reduce the possibility of heat transfer by conduction between the solid and the couple. Temperature levels and differences were so low that heat transfer by radiation would be very small.

The visual observation of total bed depth, necessary in the calculation of A' was subject to error. Special care was taken to obtain reproducible results, and in most cases the error in A', and hence in h_g, was less than 5%. In a few instances, corresponding to the highest gas velocities, a maximum uncertainty in A' of 10% was possible.

Nonuniform rates of evaporation from the particle surface are possible and would indicate an error in A' and h_g. This possibility was combatted by careful wetting of the solids to try and obtain uniform water content. Agreement between the results for alumina and silica gel, and the reproducibility of the data for any one material, are a measure of the magnitude of this error.

Results. A summary of the heat transfer coefficients and the data from which they were computed are given in Table 1. For any one particle-size range, h_g increases with the superficial mass velocity. This is indicated in Figure 4 where the silica gel data for three different particle-size ranges are shown. It is also apparent from the figure that the heat transfer coefficient increases as the average particle size increases. To correlate empirically the effects of both mass velocity and particle size, the results were replotted using the Nusselt group and the modified Reynolds number. All data, for both silica gel and alumina, are shown plotted in this way in Figure 5. The solid line corresponds to the equation

$$\frac{h_g d_p}{k} = 0.0135 \left(\frac{d_p G}{\mu} \right)^{1.30} \qquad (6)$$

and correlates the data with an average deviation of 6.3% and a maximum deviation of 17%.

Equation (6) does not include all the variables that affect the heat transfer coefficient in fluidized beds. For example, preliminary measurements with more dense materials indicate that an increase in density increases h_g. However, the difference in densities between alumina and silica gel was not sufficient to produce a significant effect. Within the accuracy of the data the heat transfer coefficient for silica gel and alumina were the same. Void space is another factor that would be expected to influence h_g. Although the extreme variation in per cent void space was from 60 to 80, it was not possible to isolate a definite trend of the results with this variable.

Discussion. The low magnitude of the heat transfer coefficients is the most striking feature of the results. It is not possible to make a direct comparison of experimental coefficients for fluidized and fixed beds, because of the difference in particle size and the difficulty in evaluating the relative velocity or slip velocity of gas past the particles in the fluidized case. However, at the same particle size and at the same superficial mass velocity, extrapolation of the Hougen and Wilke (*7*) data for packed beds gives heat transfer coefficients several times larger than those reported here. This would be expected because of the tendency of the particles in the fluidized bed to move with the gas and, therefore, reduce the slip velocity to a value lower than that in packed beds. The concept that the average velocity of the gas past the particles must be the same in the two cases, because there is no net movement of the solid particles in a fluidized bed (batch operation) does not seem sound, since it fails to take into account the basic cause of the motion of the particles. Inasmuch as fluidization occurs at gas flow rates considerably lower than the free fall value predicted from Stokes law, the movement must be attributed to the existence of local velocities higher than the average across the entire bed. Variations in velocity occur because the gas flow is not laminar; vortex forma-

tion and eddy currents give rise to nonuniform velocities in the direction of flow and velocity components perpendicular to that direction. The observation that the solid particles are in rapid motion, and move in a horizontal as well as a vertical direction in the bed, must result from the tendency of the particles to follow the gas eddies in the bed. This movement with the gas means a small slip velocity and a correspondingly small heat transfer coefficient between particle and gas. There is evidence substantiating the existence of eddy currents in fluidized beds from the work of Gilliland and Mason (*2*). By use of a tracer gas they showed that there was significant down-mixing of the gas in a fluidized bed and computed eddy diffusivity coefficients from their data. Near the tube wall the average upward gas velocity is low and high local velocities not as common as near the center of the tube. Therefore, the solid particles tend to fall near the wall and tend to rise near the center.

Except possibly at low gas flow rates, the pressure drop per unit height through a fluidized bed is less than in a packed bed at the same gas mass velocity. Loss in pressure in both cases is primarily due to turbulence and to friction between the gas and particle. While a low turbulence contribution to the pressure drop might be explained because of a higher void space than in a packed bed, the low friction contribution suggests a low slip velocity. This lower slip velocity and accompanying lower heat transfer coefficient for fluidized beds are in qualitative agreement with the data reported here.

The increase in heat transfer coefficient with particle size, and apparently with particle density, is compatible with the concept that the solids tend to move with the gas. From the point of view of Stokes law, large particles will have a higher slip velocity than small particles at a constant mass velocity of gas; or considered from a different point of view, to maintain the same condition of fluidization, a larger mass velocity is required for the large particles. Both of these approaches lead to the conclusion that the heat transfer coefficient should increase with particle size.

By adsorption of lead nitrate on alumina it was possible to increase the solid density to 2.3 in comparison with 1.6 for plain alumina. Incomplete test data indicate an increase in heat transfer coefficient of about 25% with the heavy alumina. This result would be expected since the slip velocity would increase as the density increases, at the same mass velocity.

Mass Transfer Coefficients

Method of Calculation. Mass transfer coefficients were evaluated by taking the equilibrium pressure of the water vapor on the particle surface equal to the partial pressure of water vapor in the air leaving the fluidized bed. (This assumption is analogous to that of a constant particle surface temperature t_s used in the heat transfer calculations.) Then the partial pressure in the air, at the points in the bed for which the temperature was known, was computed by a heat balance (based upon adiabatic conditions) according to the equation,

$$Gc_p(t_{g1} - t_g) = (\Delta H)\left(\frac{p_g}{P - p_g} - \frac{p_{g1}}{P - p_{g1}}\right)\frac{18G}{29} \qquad (7)$$

Conditions at the bed inlet are denoted by the subscript 1, while p_g and P represent the partial pressure of water vapor and the total pressure, respectively, at any point in the bed. From this information, charts of p_g vs. x were prepared for each run and the mass transfer coefficient k_g determined by graphical integration using the following equation (analogous to Eq. (2))

$$k_g = \frac{w}{A'\int_o^{x_e}(p_g - p_s)dx} \qquad (8)$$

The symbol w represents the molal rate of desorption of water from the bed.

As pointed out by Sherwood (*5*), in measuring transfer rates for the evaporation of water into air, h_g and k_g are based upon the same experimental data and one coefficient can be computed from the other. In other words, instead of using Equation (8), the mass transfer coefficient could have been determined directly from h_g as follows:

$$k_g = \frac{h_g}{c_p M_a p_m} \qquad (9)$$

Results. Mass transfer coefficients computed according to Equation (8) are shown in Table 1. The influence of mass velocity and particle size were correlated by use of the dimensionless group, $\frac{k_g p_m M_a}{G}$, and the Reynolds number. Data are shown plotted in terms of these groups in Figure 6. The straight line on the chart corresponds to the equation,

$$\frac{k_g p_m M_a}{G} = 0.00180\left(\frac{d_p G}{\mu}\right)^{-0.30} \qquad (10)$$

where p_m and M_a represent the mean partial pressure and the molecular weight of air, respectively.

Acknowledgment

This investigation was made possible by funds from the Research Corporation through a Frederick Gardner Cottrell Grant-in-Aid.

Notation

A = area of surface of fluidized particles for heat or mass transfer, sq.ft.

A' = area of fluidized particles per unit bed height, i.e., A/x

c_p = specific heat of air, B.t.u./(lb.)(° F.)

d_p = diameter of solid particle, ft.

G = superficial mass velocity, lb./(hr.)(sq.ft.)

h_g = gas film heat transfer coefficient, B.t.u./(hr.)(sq. ft.)(° F.)

ΔH = heat of vaporization of water, B.t.u./lb.

k = thermal conductivity, B.t.u./(hr.)(ft.)(° F.)

k_g = gas film mass transfer coefficient, lb. moles/(hr.)(sq. ft.)(atm.)

m = mass of fluidized material, lb.

M_a = molecular weight of air, lb./lb. mole

p_g = partial pressure of water vapor in air stream, atm.; p_{g1}—partial pressure at entrance to bed

p_s = partial pressure of water vapor at particle surface, atm.

p_m = mean partial pressure of air in bed, atm.

P = total pressure, atm.

q = rate of heat transfer in fluidized bed, B.t.u./hr.

r = radius of solid particle (assumed spherical), ft.

t_g = gas temperature, ° F.

t_s = solid particle temperature, ° F.

w = rate of water desorped from solid particles, lb.moles/hr.

x = height of fluidized bed, ft.

x_e = height of bed required to reach equilibrium conditions

x_t = total bed height

Greek Letters:

μ = viscosity of gas, lb./(hr.)(ft.)

ρ_s = density of fluidized material lb./cu.ft.

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Discussion

C. F. Bonilla (Columbia University, New York, N. Y.): In computing the mean coefficient of heat transfer, the differential equation for heat flow, $dq = h\Delta t dA$, can, theoretically, be integrated in either of two ways. If Δt is known as a function of A the equation may be separated as follows:

$$\int \Delta t dA = \int \frac{dq}{h} = \frac{q}{h_m}$$

giving an h averaged (reciprocally) over q, which is what the authors have computed. If Δt is known as a function of q, the equation may be separated:

$$\int \frac{dq}{\Delta t} = \int h dA = h_m A$$

giving an h averaged over the area. The important consideration is that only the latter average h is useful for design purposes, since Δt will not be known ahead of time as a function of A, but only of q, and the two values are numerically not equal unless Δt is constant, which is far from true in the present case.

I believe, therefore, that in spite of minor errors that might be introduced in this case by computing q from the flow rate and temperature rise of the air stream, a more useful, and in this sense accurate, value of h_m would be obtained by employing the second method over part of the column than the first method over all of it. The equation would be expressed

$$h_m = \frac{W}{A} \int \frac{s dt}{\Delta t}$$

where s is the humid heat and W the pounds per hour of bone dry air. Evidently the whole column can not be employed because Δt is reported to reach to zero, within the accuracy of the temperature measurements. Probably the bottom half of the column would be a desirable portion to use.

An alternative and theoretically even more desirable procedure, if it is felt that the air temperature curve can be drawn or fitted reliably enough, is to compute the local h at several positions in the botom half or so for each run by:

$$h = \frac{1}{\Delta t} \frac{dq}{dA} = \frac{Ws}{\Delta t} \frac{dt}{dA}$$

These local values of h, if reliable enough, should correlate as j factors at local conditions better than the average values at "average conditions."

K. N. Kettenring: You mentioned the fact that it could be integrated over, say, a 1-in. depth. Unfortunately, we could not do that, because our transfer was based upon a measurement of the total water evaporated from the bed. Therefore, a heat transfer over the 1 in. of bed, we could not use with the value we had for q.

C. F. Bonilla: Yes, you could, because you have the temperature of the gas. You could compute q from the temperature of the gas.

K. N. Kettenring: We did not have quite adiabatic conditions, and the change in temperature of the gas is not as good a value as the amount of heat calculated on the basis of the water evaporated, because this is an exact measurement of the amount of heat transferred across the bed.

R. V. Jelinek (Columbia University, New York, N. Y.): You mentioned that your surface areas were calculated by assuming that the particles were spheres. Is that right?

K. N. Kettenring: Yes.

R. V. Jelinek: For a porous material like silica or alumina gel, don't you think it would be better to use a more accurate estimate, like the B.E.T. Method of low-temperature nitrogen adsorption, which gives you a more accurate measure of the area?

K. N. Kettenring: The surface for evaporation does not include the core areas which would be included in gaseous means of determination. There is some difference of opinion among authors on what the correct surface area is. Therefore, we used an approximation, which is admittedly an approximation, and could be corrected by a shape factor for the type of surface and particle shape.

Anonymous: Was there any particular agitation or turbulence noted in the bed of particles when you were measuring heat transfer coefficient.

K. N. Kettenring: Of course, it was a fluidized bed. There was agitation and turbulence at all times.

Anonymous: That was the point I was trying to get at. Rough calculation just showed that the velocity was something like a tenth of a foot, or two-tenths of a foot, a second for rather large particles, and I think if you had used smaller particles at a little higher velocity, you might have had better heat transference.

K. N. Kettenring: Smaller particles were not used because we could not, with our means of measurement, measure the changes quickly enough, and the velocities used were those from the minimum, which merely kept the material in motion, to the maximum, which blew it to the top and stopped the flow through the screen.

Anonymous: With small diameter particles, I think it is pretty well known that heat transfer due to conduct alone can be very high. For a 10 to 50μ particle, the heat transfer coefficient per unit of surface would be of an order of magnitude higher than has been indicated in this work.

K. N. Kettenring: These heat transfer coefficients compare favorably with values for conduction alone to particles of approximately 14-20 mesh, as calculated by us.

Anonymous: On the plot that you showed, I noticed that the equilibrium was at the 2-in. bed height. What was the variation with your different runs in that bed height?

K. N. Kettenring: The bed height varied from 4 to 8 in., or slightly more if you included the less dense phase.

Anonymous: Take just the part required for equilibrium, which was the amount you referred to. That was 2 in. What was the variation in that—all the way up to the complete height of the bed?

K. N. Kettenring: No; in some runs that varied between 1½ and 2 in.

Anonymous: Apparently, the results, then, are independent of the bed height.

K. N. Kettenring: They were calculated on the basis of whatever bed height was present at that time.

Anonymous: The previous speaker mentioned that his results were independent of the diameter of his column, which in that case was a pipe, and also independent of the bed height, and I wanted to see how you felt about it.

K. N. Kettenring: He was talking about a different heat transfer coefficient, if you remember, the transfer from the outside through the walls. Of course, the amount of heat transferred varies with the bed height unless equilibrium is reached.

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(Presented at Forty-first Annual Meeting, New York, N. Y.)

DETERMINATION OF MECHANISM OF CATALYZED GASEOUS REACTIONS

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IN the industrial applications of kinetics a knowledge of the mechanisms of chemical reactions is helpful in establishing the optimum conditions of operation relative to such variables as pressure, temperature, feed composition, space velocity, extent of conversion, and recycling.

This paper is written as a guide in the planning of experimental programs in applied kinetics and as an aid to the selection of the mechanisms of catalytic reactions. It has been observed that much time is lost in failing to pursue an orderly experimental program, and in failing to recognize the important variables. Often it is discovered after years of experimental effort that the important variables were not investigated.

In a previous paper by Hougen and Watson (*2*) various mechanisms which may be encountered in gaseous reactions when catalyzed by solid surfaces were developed with appropriate mathematical equations for expressing rates.

In a large measure the concepts of chemical kinetics used in this paper also stem from the work of Eyring and associates.

In any given chemical process several reactions may be proceeding consecutively or simultaneously but for each reaction it may be assumed that only one or two chemical steps are rate-controlling. From the standpoint of theoretical kinetics this assumption is not acceptable, but it usually serves as a satisfactory basis for practical purposes.

Where a gaseous reaction is catalyzed by flowing the gas through a bed of solid catalyst pellets, the physical steps involved are the transfer of the component gases up to the catalyst surface, diffusion of reactants into the interior of the pellet, diffusion of products back to the exterior surface, and transfer of the products from the exterior surface to the main stream. These physical steps are usually present. To simplify the interpretation of experimental data it is desirable to minimize the resistance offered by each of these physical steps and thus to deal only with the chemical aspects of the reaction.

The chemical steps involve activated adsorption of reactants with or without dissociation, surface reactions on active sites, and activated desorption of products. The uncatalyzed reaction also takes place in the main gas stream simultaneously with the surface reaction. This last should be of negligible importance where an effective catalyst is used.

In addition to the above possibilities, fouling and changes in the activity of the catalyst may take place.

It is evident that an experimental study of all these possible effects simultaneously is prohibitive because of complexity. It is desirable, therefore, that experimental procedures be arranged to permit separate determination or separate elimination of these different effects. Resistances to the transfer of mass and heat can be minimized by operating at sufficiently high mass velocities to make the partial pressure and temperature gradients across the gas film negligible. The retarding effect of diffusion of reactants and of products in the interior of the catalyst pellet can be minimized by using pellets of small size. The effect of fouling can be eliminated by extrapolating rate data to the beginning time of catalyst service and the effect of changing activity can be eliminated by continued use of the catalyst until a stable steady state has been attained.

The means of minimizing the various physical steps and the effects of fouling and deactivation will be analyzed separately.

Minimizing Resistances Due to Transfer of Mass and Heat. The general rate of a catalytic reaction in a flow system based upon unit mass of catalyst is given by the relation,

$$r_A dW = F dx_A \qquad (1)$$

where

r_A = moles of reactant A converted per (unit time) (unit mass of catalyst)

F = flow rate of feed, moles per unit time

W = mass of catalyst

x_A = moles of reactant A converted per mole of feed

Values of the reaction rate r should be correlated against the conditions of composition and temperature which prevail at the surface of the catalyst where the catalytic reaction actually takes place. From equations for mass and heat transfer the film gradients for partial pressures of each component gas and for temperature can be evaluated. However, this correction is troublesome, difficult, and uncertain. In experimental work it is desirable, if possible, to render these gradients insignificant by flowing the gas at high mass velocities. If the rate of a catalytic reaction is plotted against mass velocity the rate increases progressively from a value at zero mass velocity to an asymptotic value at high velocities as shown in Figure 1. It is desirable to operate at sufficiently high velocities so that film gradients become negligible. The value of r at zero mass velocity is the reaction rate obtained in a nonflow system. It is evident from Figure 1 that reaction rates calculated from equal residence times in nonflow and flow systems are not the same. In general catalytic reaction rates obtained in nonflow systems are not applicable directly to flow systems. Indeed it is doubtful if reaction rate data taken in nonflow systems of gases catalyzed by solid surfaces and without agitation in the reactor are of any value in reactor design because of nonsteady state conditions and the uncertainty of concentration gradients due to natural convection within the bed.

The general equation for mass transfer is given as

$$r = k_G a_m \Delta p \qquad (2)$$

where

$$\Delta p = p_A - p_{Ai}$$

Experimental data on mass transfer are related to k_G by the relationship:

$$j_d = \left(\frac{k_G M_m p_f}{G}\right)\left(\frac{\mu}{\rho D_{Am}}\right)_f^{2/3} \qquad (3)$$

Experimental data on values of j_d were obtained for mass transfer in a granular bed by Gamson, Thodos, Wilke, and Hougen (*1, 6*) and related to a modified Reynolds number $\frac{\sqrt{a_p}G}{\mu}$ as follows:

$$j_d = a\left(\frac{\sqrt{a_p}G}{\mu}\right)^{-n}$$

where for values of $\frac{\sqrt{a_p}G}{\mu}$ less than 620, $a = 2.44$ and $n = 0.51$; and for values of $\frac{\sqrt{a_p}G}{\mu}$ greater than 620, $a = 1.25$ and $n = 0.41$.

By a combination of Equations (*2*), (*3*), and (*4*) there results:

$$\frac{\Delta p_A}{p_A} = \frac{1}{a}\left(\frac{\sqrt{a_p} r M_m p_f}{p_A \mu a_m}\right)\left(\frac{\mu}{\rho D_{Am}}\right)_f^{2/3}\left(\frac{\sqrt{a_p}G}{\mu}\right)^{n-1} \qquad (5)$$

In Figure 2 values of $\Delta p_A/p_A$ are plotted against values of a reaction rate number X for different values of $\sqrt{a_p}G/\mu$ where

$$X = \left(\frac{\sqrt{a_p} r M_m p_f}{p_A \mu a_m}\right)\left(\frac{\mu}{\rho D_{Am}}\right)_f^{2/3}$$

In Figure 3 values of $\Delta p_A/p_A$ over the limited range 0 to 0.1 are similarly plotted. Figure 4 is a cross plot of Figure 3 where X is plotted against values of $\sqrt{a_p}G/\mu$ for values of $\Delta p_A/p_A$ equal to 0.1 and below. If the required experimental accuracy in reaction rates need not be greater than 10% then the film gradient can be neglected if $\Delta p_A/p_A$ is 0.1 or less; for an accuracy of 1% the film gradient can be neglected if $\Delta p_A/p_A$ is 0.01 or less, and so forth.

The film gradients become negligible where surface reactions proceed slowly and also at high partial pressures of the reactants. For example, from Figure 4 the following conditions prevail:

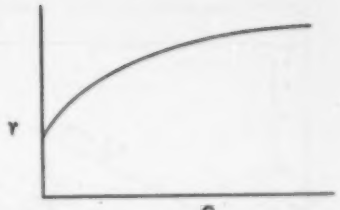


Fig. 1. Effect of Mass Velocity Upon Reaction Rates.

$\frac{\Delta p_A}{p_A}$	X	$\frac{\sqrt{a_p}G}{\mu}$
0.1	5	450
0.1	10	1700
0.01	5	25,000
0.01	10	80,000

Thus, if an accuracy of 10% is tolerated where the rate number X is 5, the modified Reynolds number should not be less than 450, whereas if 1% accuracy is required the modified Reynolds number should not be less than 25,000 for the same rate number.

The rate of mass transfer becomes entirely rate-controlling where $p_{Ai} = 0$ and $\Delta p_A/p_A = 1.0$. This limiting condition is approached with an ideal catalyst where surface reactions are instantaneous. Under these conditions the reac-

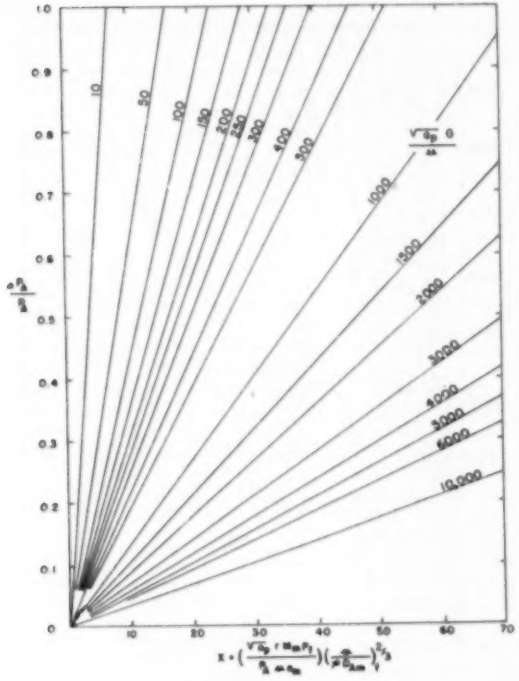


Fig. 2. $\frac{\Delta p_A}{p_A}$ **versus** X.
($\Delta P_A/P_A$ range 0 to 1.0)

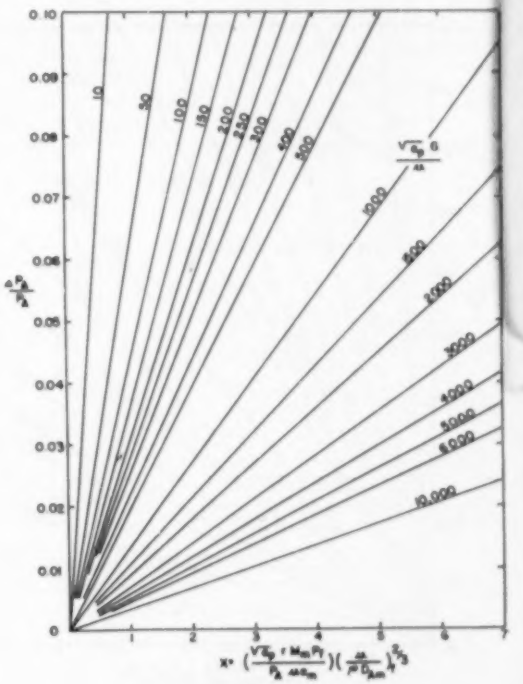


Fig. 3. $\frac{\Delta p_A}{p_A}$ **versus** X.
($\Delta P_A/P_A$ range 0 to 1.0)

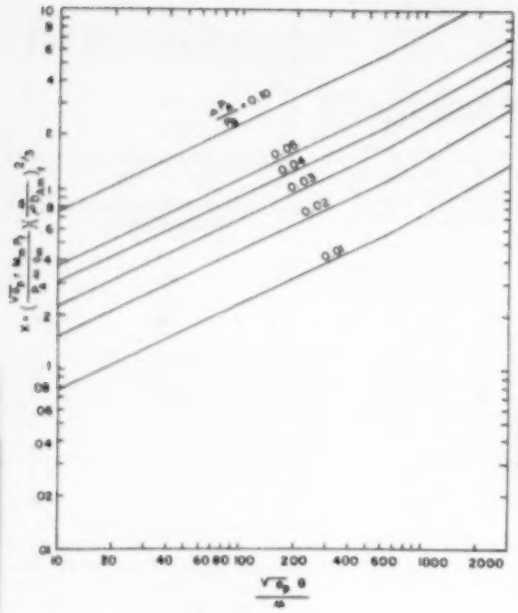


Fig. 4. X versus $\frac{\sqrt{a_p G}}{\mu}$ at Various Values of $\Delta P_s/P_s$.

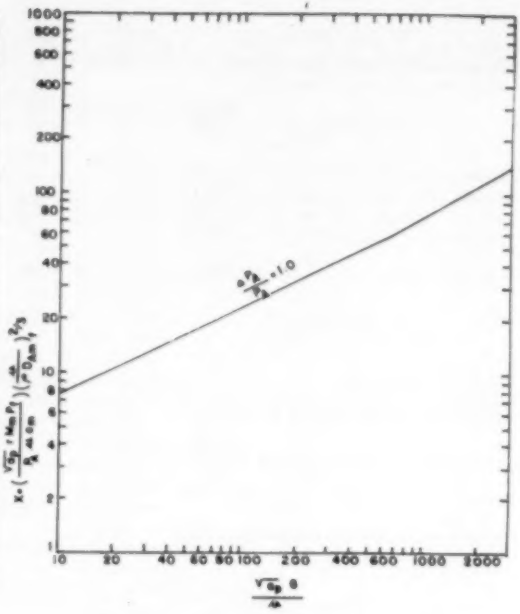


Fig. 5. Limiting Values at X versus $\frac{\sqrt{a_p G}}{\mu}$

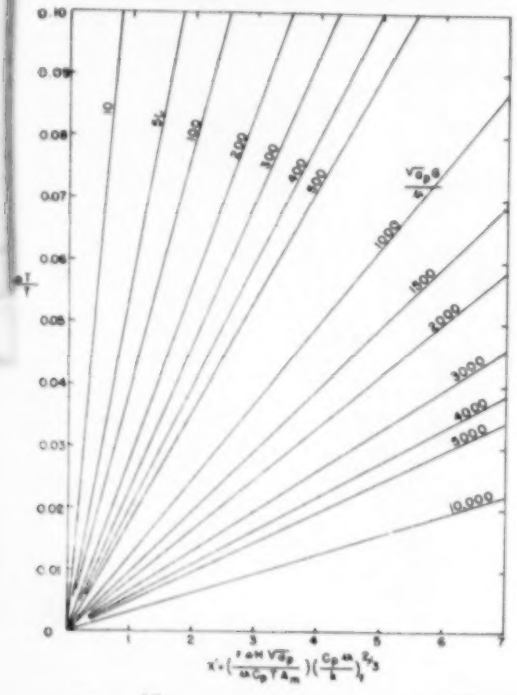


Fig. 6. $\frac{\Delta T}{T}$ versus X' at Various Values of $\frac{\sqrt{a_p G}}{\mu}$

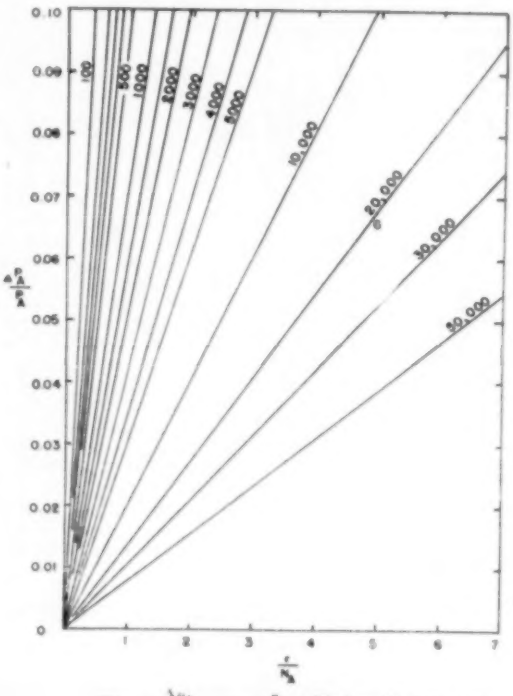


Fig. 7. $\frac{\Delta p_s}{p_s}$ versus $\frac{r}{N_s}$ at Various Values of G.

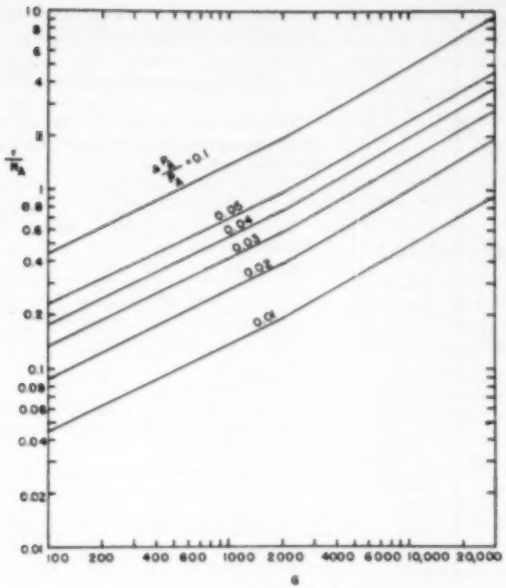


Fig. 8. $\frac{r}{N_A}$ versus G at Various Values of $\Delta P_A/P_A$ for a Specific System.

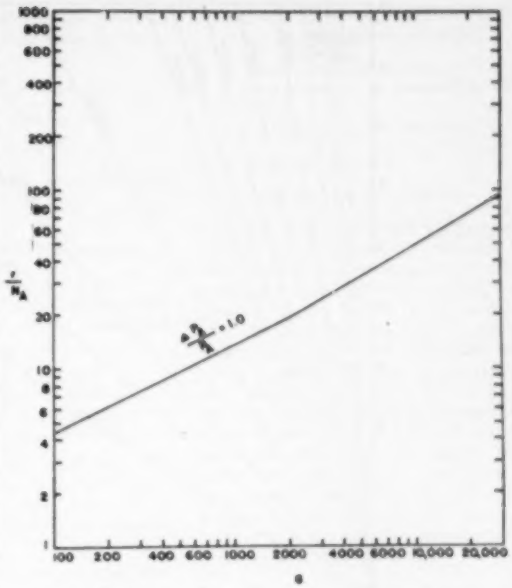


Fig. 9. Limiting $\frac{r}{N_A}$ versus G for a Specific System.

tion rate is controlled entirely by the rate at which the reactants can be brought up to the surface and the products returned. Equilibrium prevails at the interface. This limiting rate is shown by the relationships of Figure 5. Thus from Figure 5 mass transfer becomes entirely controlling and the rate number X cannot exceed the values given for the following modified Reynolds number:

$\frac{\sqrt{a_p}G}{\mu}$	X
10,000	200
1,000	74
100	23
10	7.5

For example, when the modified Reynolds number is 100 the rate number X cannot exceed 23, which condition corresponds to the behavior of an ideal catalyst.

The general equation for heat transfer is given as

$$q = -h_G a_m \Delta t = -\Delta H r \qquad (6)$$

$$\Delta t = t - t_i$$

Experimental data on heat transfer are related to h_G by the relationship,

$$j_h = \left(\frac{h_G}{C_p G}\right)\left(\frac{C_p \mu}{k}\right)_f^{2/3} \qquad (7)$$

Experimental data on j_h were obtained for heat transfer in a granular bed (*1, 6*) and related as follows:

$$j_h = a'\left(\frac{\sqrt{a_p}G}{\mu}\right)^{-n} \qquad (8)$$

where for values of $\sqrt{a_p}G/\mu$ less than 620, $a' = 2.62$, $n = 0.51$, for values of $\sqrt{a_p}G/\mu$ greater than 620, $a' = 1.35$, $n = 0.41$. By a combination of Equations (6), (7), and (8) the result is

$$\frac{\Delta t}{T} = \frac{1}{a'}\left(\frac{r\Delta H\sqrt{a_p}}{a_m \rho C_p T}\right)\left(\frac{C_p\mu}{k}\right)_f^{2/3}\left(\frac{\sqrt{a_p}G}{\mu}\right)^{n-1} \qquad (9)$$

In Figure 6 values of $\Delta t/T$ are plotted against X' for various values of $\sqrt{a_p}G/\mu$ where

$$X' = \left(\frac{r\Delta H\sqrt{a_p}}{a_m C_p T}\right)\left(\frac{C_p\mu}{k}\right)_f^{2/3}$$

Film temperature gradients can be neglected if they do not exceed a few degrees Centigrade. If the required accuracy in reaction rates need not be greater than 10% then the film temperature gradient can usually be neglected if ΔT is less than 10° C. These values require verification for specific systems. It should be recognized that the temperature coefficient for reactions catalyzed by solid surfaces is much less than for noncatalytic ones because of the offsetting effects of desorption on the catalytic reactions.

A Hypothetical System. For a hypothetical system the following conditions were:

Cylindrical pellets $\frac{1}{16} \times \frac{1}{16}$ in.,
$D = \frac{1}{16}$ in.; $D_p = \sqrt{1.5}\,D = 0.0127$ ft.

$a_p = \pi D_p^2 = 0.000507$ sq.ft.

$\mu = 300$ micropoises $= 0.0726$ lb./(hr.)(ft.)

$F_c = 0.40$

$a_c = \frac{6(1 - F_c)}{D} = 346$ sq.ft./cu.

$\rho_B = 50$ lb./cu.ft.

$a_m = \frac{a_c}{\rho_B} = 6.92$ sq.ft./lb.

$M_m = 50$

$p_f = \pi$

π = total pressure

$\Delta H = -10{,}000$ B.t.u./lb. mole A converted

$\left(\frac{\mu}{D_{Am}}\right)_f = 1.50$

$\left(\frac{C_p\mu}{k}\right)_f = 0.80$

$C_p = 0.70$ B.t.u./(lb.)(° R.)

at $\frac{\sqrt{a_p}G}{\mu} = 620$; $G = 2{,}000$ lb./(hr.)(sq.ft.)

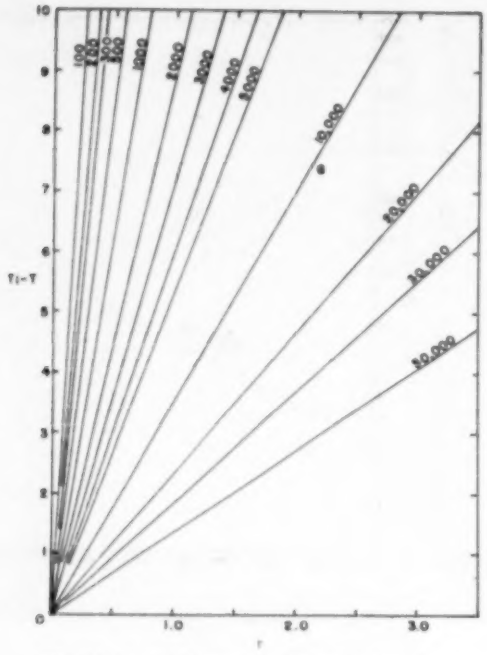


Fig. 10 $(T_i - T)$ Versus r at Various Values of G.

$$N_A = \frac{f_A}{\pi}$$

Then

$$\frac{\Delta p_A}{p_A} = \frac{a'' r}{N_A G^{(1-n)}}$$

where

at values of $\sqrt{a_p} G/\mu < 620$;

$$a'' = 2.15;\ n = 0.51$$

at values of $\sqrt{a_p} G/\mu > 620$;

$$a'' = 4.70;\ n = 0.41$$

For this system values of $\Delta p_A/p_A$ are plotted against r/N_A for the various parameters of G (Fig. 7) for values of $\Delta p_A/p_A$ ranging from 0 to 0.1 and values of r/N_A are plotted against G for various parameters of $\Delta p_A/p_A$ in Figure 8. From Figure 7 the following values are obtained from this special system:

$\frac{\Delta p_A}{p_A}$	$\frac{r}{N_A}$	G
0.1	5	11,000
0.01	1	35,000

Thus if an error of 10% is tolerated the film gradient for mass transfer can be neglected for a reaction rate r/N_A equal to 5 when the mass velocity G is 11,000 lb./(hr.)(sq.ft.) or greater.

If the reaction at the catalyst surface is instantaneous then the ratio of $\Delta p_A/p_A$ becomes equal to 1.0 and the rate depends upon mass transfer alone. For this specific system this case is plotted in Figure 9 and values of Δt are plotted against r for various parameters of G in Figure 10.

For this special system mass transfer becomes entirely controlling and the reaction rate r/N_A cannot exceed the following values for the given mass velocities (Fig. 9):

$\frac{\Delta p_A}{p_A}$	G	$\frac{r}{N_A}$
1.0	100	4.46
1.0	1,000	13.7
1.0	10,000	49.2

In order to keep the film temperature drop below 10° C. for this specific system at a reaction rate of $r = 1.0$, the mass velocity G should be 1600 or greater (Fig. 10).

It should be noted that the relationships given in Figures 2-10 are based upon experimental work for water vapor-air mixtures at relatively low temperatures and extrapolated through generally accepted relationships of the transport properties of gases. Extensive experimental work in this field should be encouraged to give greater certainty.

Effect of Size of Catalyst Pellet. The relationship between the effectiveness factor of a catalyst and its modulus are expressed by the relationship of Equation (10) first developed by Thiele (*4*) for a first-order gaseous reaction neglecting the effects of activated adsorption and variations in the porosity and permeability within a single pellet.

$$E = \frac{3}{m^2}\,(m\ coth\ m - 1) \quad (10)$$

The modulus m may be related to pellet size, porosity, and temperature by the following (*2*):

$$m = \frac{a_1 D'_p e^{b/T}}{\sqrt{F_i}} \quad (11)$$

where

D'_p = diameter of sphere having the same surface area per unit volume as the particle. For a cylinder of height D equal to diameter,

$$D'_p = D = \frac{6}{a_m \rho_p}$$

F_i = interior void fraction of the pellet

ρ_p = density of pellets, mass per unit volume

By using two pellets of identical composition, porosity, and temperature but of different sizes the ratio of moduli is

$$\frac{m_1}{m_2} = \frac{D_1}{D_2} = a \quad (12)$$

By establishing reaction rates for two runs at nearly identical conditions of gas temperature and composition at the surface of the catalyst with these two pellets the following ratio prevails:

$$\frac{r_1}{r_2} = \frac{E_1}{E_2} = b \quad (13)$$

From Equations (10), (12), and (13),

$$am_2\ coth\ am_2 - 1 = ba^2(m_2\ coth\ m_2 - 1) \quad (14)$$

From Equations (14), m_2 can be calculated and m_1, E_1, and E_2 from Equations (10), (12), and (13).

The effectiveness factor approaches unity as the particle size is reduced. For establishing rate mechanisms it is desirable to operate with small catalyst pellets in order to minimize the effects of diffusional gradients inside the pellet and to attain effectiveness factors approaching unity. This procedure also minimizes the uncertainties due to time lag in attaining the steady state and to the assumptions made in deriving the relationship of E to m. Cylinders $\frac{1}{8} \times \frac{1}{8}$ in. seem to be the smallest size which can be economically pelleted and used in a stationary bed and at the same time permit high mass velocities without excessive pressure drops and losses by attrition.

Effect of Fouling. Where fouling of a catalyst occurs it is desirable to extrapolate rates to zero time of service and to make all correlations on the fresh catalyst. This introduces an uncertainty

due to the lack of steady conditions in starting a run. Where these difficulties become insurmountable it is necessary to find a temperature range where fouling is negligible.

Effect of Changing Activity of Catalyst. The activity of a catalyst changes due to deactivation caused by employment of excessive temperatures and by poisoning. Where the feed consists of different streams for the separate reactants the poisoning component in each stream can be removed often by passing each stream separately through a special bed of the same catalyst before the reaction takes place. This proves effective if the poison is present in small traces.

C. C. Watson and Stevens (*3*) have shown in an unpublished thesis that steady-state conditions cannot be attained until the catalyst attains chemical equilibrium with the gas stream; this is in addition to the attainment of physical equilibrium in temperature and concentration gradients through the catalyst. The effect of changing activity can be eliminated by continuous use of the catalyst until complete equilibrium is attained both chemical and physical. This may introduce a serious time lag where composition and temperature of the gas stream are changed from run to run. It may prove impossible with some reactions to eliminate both fouling and lack of equilibrium.

Determination of Rate-Controlling Chemical Step. When effects of heat and mass transfer, diffusion, fouling, and deactivation have been minimized, eliminated, or accounted for, selection of the rate-determining chemical step is in order. Complex chemical processes may be considered as consisting chiefly of a combination of separate bimolecular and unimolecular reactions and for complex reactions the rate equations may not be related to the over-all stoichiometric relations. For gaseous reactions catalyzed by solid surfaces each separate molecular change usually consists of one or two rate-controlling chemical steps such as chemisorption with or without association of one or both reactants; surface reaction between adsorbed reactants and products, and impact of a nonadsorbed component with one that is adsorbed.

Mathematical expressions for rate equations can be derived from the principles given (*2*). In general these rates may be expressed by a combination of three terms, the kinetics term, the potential term, and the adsorption term, arranged thus,

$$r = \frac{(\text{kinetics term})(\text{potential term})}{(\text{adsorption term})^n} \qquad (15)$$

These terms are summarized herewith for the following four types of reactions:

(I) $A \rightleftarrows R$; (II) $A \rightleftarrows R + S$;

(III) $A + B \rightleftarrows R$; and

(IV) $A + B \rightleftarrows R + S$

and for the following rate-controlling mechanisms.

Rate-Controlling Mechanisms

A. Reaction between molecularly adsorbed reactants and products without dissociation of any component upon adsorption

- a. Adsorption of A controlling
- b. Adsorption of B controlling
- c. Desorption of R controlling
- d. Surface reaction controlling

B. Reaction between atomically adsorbed A, where B, R, and S are molecularly adsorbed. Upon dissociation A is adsorbed on adjacent sites.

- e. Adsorption of A controlling (with dissociation)
- f. Adsorption of B controlling
- g. Desorption of R controlling (or S)
- h. Surface reaction controlling

C. Reactant B is not adsorbed, A, R, and S are molecularly adsorbed

- i. Adsorption of A controlling
- j. Desorption of R controlling
- k. Surface reaction controlling

D. Reactant B is not adsorbed, A is atomically adsorbed, R and S are molecularly adsorbed. Upon dissociation A is adsorbed on adjacent sites

- l. Adsorption of A controlling
- m. Desorption of R controlling
- n. Surface reaction controlling

E. Reactant A is not adsorbed, B, R, and S are molecularly adsorbed

- o. Impact of A controlling
- p. Desorption of R controlling (or S)
- q. Adsorption of B controlling

F. Uncatalyzed Reaction

- r. Homogeneous gas reaction

As the field of applied kinetics develops it may be found that examples of some of these mechanisms as rate-controlling steps will not be discovered. For example, the assumption of adsorption as a rate-controlling step over the entire composition range for a bimolecular reaction is untenable. Rate of adsorption of A reaches a maximum for the pure gas, but obviously there is no reaction in the absence of B and the adsorption of A will stop when the catalyst becomes saturated with A. Under these circumstances the rate of adsorption diminishes to zero without any reaction. From this it follows that two chemical steps become rate-controlling.

Driving Potential Term. The driving potential in any rate equation fulfills the conditions of becoming zero at conditions of equilibrium where the equilibrium constant K is related to the appropriate activity ratio for the over-all reaction. For example, for the reaction $A + B \rightleftarrows R + S$ the driving potential is zero where

$$a_A a_B = \frac{a_R a_S}{K} \quad \text{or} \quad K = \frac{a_R a_S}{a_A a_B}$$

in accordance with the definition of the equilibrium constant for the over-all reaction. These driving potentials are summarized in Table 1 for the four reactions and various mechanisms.

Kinetic Term. The designation, "kin-

TABLE 1. DRIVING POTENTIAL TERMS

Reaction	$A \rightleftarrows R$	$A \rightleftarrows R+S$	$A+B \rightleftarrows R$	$A+B \rightleftarrows R+S$
Adsorption of A controlling	$a_A - \frac{a_R}{K}$	$a_A - \frac{a_R a_S}{K}$	$a_A - \frac{a_R}{K a_B}$	$a_A - \frac{a_R a_S}{K a_B}$
Adsorption of B controlling	0	0	$a_B - \frac{a_R}{K a_A}$	$a_B - \frac{a_R a_S}{K a_A}$
Desorption of R controlling	$a_A - \frac{a_R}{K}$	$\frac{a_A}{a_S} - \frac{a_R}{K}$	$a_A a_B - \frac{a_R}{K}$	$\frac{a_A a_B}{a_S} - \frac{a_R}{K}$
Surface reaction controlling	$a_A - \frac{a_R}{K}$	$a_A - \frac{a_R a_S}{K}$	$a_A a_B - \frac{a_R}{K}$	$a_A a_B - \frac{a_R a_S}{K}$
Impact of A controlling (A not adsorbed)	0	0	$a_A a_B - \frac{a_R}{K}$	$a_A a_B - \frac{a_R a_S}{K}$
Homogeneous reaction controlling	$a_A - \frac{a_R}{K}$	$a_A - \frac{a_R a_S}{K}$	$a_A a_B - \frac{a_R}{K}$	$a_A a_B - \frac{a_R a_S}{K}$

TABLE 2. KINETIC TERMS.

Multiply each of the terms below by EL except for the homogeneous reaction.

Adsorption of A controlling	k_A
Adsorption of B controlling	k_B
Desorption of R controlling	$k_R K$
Adsorption of A controlling with dissociation	$\frac{k}{2} k_A$
Impact of A controlling	$k_A K_B$
Homogeneous reaction controlling	k

Surface Reaction Controlling

	$A \rightleftarrows R$	$A \rightleftarrows R+S$	$A+B \rightleftarrows R$	$A+B \rightleftarrows R+S$
Without dissociation	$k_s K_A$	$k_s \cdot K_A$	$k_s \cdot K_A K_B$	$k_s \cdot K_A K_B$
With dissociation of A	$k_s \cdot K_A$	$k_s \cdot K_A$	$k_s \cdot (s-1) K_A K_B$	$k_s \cdot (s-1) K_A K_B$
B not adsorbed	$k_s K_A$	$k_s \cdot K_A$	$k_s K_A$	$k_s \cdot K_A$
B not adsorbed, A dissociated	$k_s \cdot K_A$	$k_s \cdot K_A$	$k_s \cdot K_A$	$k_s \cdot K_A$

tic term," includes all factors which appear in the numerator of the reaction rate equation other than the driving potential such as L, the total number of active sites; the effectiveness factor E; appropriate kinetic constants for adsorption controlling, k_A and k_B; for desorption controlling, k_R and k_S; for surface reactions controlling k_s; and for the homogeneous reaction controlling, k. The factor s represents the number of adjacent active sites. Values of L and s will usually not be known and will be included in a characteristic constant for a specific catalyst. Over-all equilibrium and adsorption equilibrium constants of the reactants A and B may also appear in the kinetic term. Factors in the kinetic term are tabulated in Table 2.

Adsorption Term. Where all reactants, products, and inerts are adsorbed under equilibrium conditions and without dissociation the adsorption term is

$$[1 + K_A a_A + K_R a_R + K_B a_B + K_S a_S + K_I a_I]^n \qquad (16)$$

Under other conditions the replacements shown in Table 3 should be made.

The exponent n of the adsorption term is equal to 1 where the reaction involves only one site, equal to 2 when reaction involves two adjacent sites, and is equal to 3 when the reaction involves three adjacent sites. The exponents take the values shown in Table 4.

Formulation of Rate Equations. From these relations the rate equation for any of the above reactions and rate-controlling mechanisms can be readily formulated. For example,

Where the reaction $A + B \rightleftarrows R + S$ is surface-controlling with equilibrium adsorption of all components,

the driving potential term is

$$a_A a_B - \frac{a_R a_S}{K} \qquad \text{(from Table 1)}$$

kinetic term is

$$L s k_s K_A K_B \qquad \text{(from Table 2)}$$

adsorption term is

$$[1 + K_A a_A + K_R a_R + K_B a_B + K_S a_S + K_I a_I]^2$$

the exponent is 2 (Table 4)

and the rate equation becomes

$$r = \frac{L s k_s K_A K_B \left(a_A a_B - \frac{a_R a_S}{K} \right)}{[1 + K_A a_A + K_R a_R + K_B a_B + K_S a_S + K_I a_I]^2} \qquad (17)$$

Where the reaction $A + B \rightleftarrows R$ proceeds with adsorption of A controlling and with dissociation of A,

the driving potential term is

$$\left(a_A - \frac{a_R}{K a_B} \right) \qquad \text{(from Table 1)}$$

the adsorption term is

$$\left[1 + \sqrt{\frac{K_A a_R}{K a_B}} + K_R a_R + K_B a_B + K_I a_I \right]^2 \qquad \text{(from Table 3)}$$

the exponent is 2 (Table 4)

and the rate equation becomes

$$r = \frac{L k_s \left(a_A - \frac{a_R}{K a_B} \right)}{2 \left[1 + \sqrt{\frac{K_A a_R}{K a_B}} + K_R a_R + K_B a_B + K_I a_I \right]^2} \qquad (18)$$

Initial Rates. Initial rates for the pure reactants present in stoichiometric proportions and in the absence of products and inerts can now be readily calculated in terms of total pressure. Thus, for Equation (17), since

$$a_A = a_B = \frac{\pi}{2}$$

and

$$a_R = a_S = 0$$

$$r_o = \frac{a\pi^2}{(1 + b\pi)^2} \qquad (19)$$

and Equation (18) reduces to

$$r_o = \frac{a\pi}{(1 + b\pi)^2} \qquad (20)$$

The remainder of this paper will be devoted to an initial selection of the most plausible mechanism from a visual inspection of the shape of rate curves when data are properly obtained to permit such plots. The actual evaluation of the appropriate constants should then be made by statistical methods of fitting data to the selected equation. From the shape of rate curves when plotted against such variables as pressure, feed composition, temperature and conversion, the most plausible mechanism of a simple reaction can be estimated. Examples given herewith are for the four molecular types of gaseous reactions cited assuming only one rate-controlling chemical step. Where several reactions are involved and where more than one chemical step is rate-controlling in each, the analysis becomes complicated. Complexities, however, can be minimized by extrapolating rates to conditions of zero reciprocal space velocity at which condition the complicating effects of several reactions have not begun.

By systematic and separate variations in pressure and feed composition, the mechanism can be fairly well established by visual inspection of the rate curve. When more than one chemical step is rate-controlling the number of constants in the rate equations becomes so numer-

ous and the accuracy of evaluation of each so uncertain that some empirical short cut may prove expedient. The effect of extent of conversion is difficult to generalize and the effect of temperature is of minor value in establishing mechanism.

Effect of Pressure. Pressure is by far the most important variable in determining the mechanism of a gaseous reaction catalyzed by a solid. Unless experiments are set up to operate with pressure as a controlled variable over a wide range it may not be possible to establish with certainty the probable mechanism. Variations in total pressure as well as partial pressures are essential. Partial pressures can be diversified by varying feed composition, but in addition the total pressure must be varied independently. For convenience the effects of total pressure will be illustrated by observing variations in the initial reaction rate with the use of fresh feed with no product present. Under these conditions the reverse reaction is negligible.

In Table 5 effects of pressure upon initial reaction rates are seen to fall into nine types of curves.

In Type *I* the initial rate, $r_o = a$ is independent of pressure. This type indicates that desorption of product K from the catalyst is the rate-controlling step when the reverse reaction is negligible. This situation occurs when all the active sites are saturated with respect to all components except product K and under initial conditions when no products have accumulated in the main gas stream. The same situation is encountered for finite values of the equilibrium constant K where a second product S is formed and adsorbed under equilibrium conditions. As the reaction proceeds with accumulation of product K in the gas stream the reaction rate is no longer constant but progressively diminishes. The value of r at zero pressure is a hypothetical initial rate of desorption. Since there is no supply of reactants at zero pressure, there is no reaction and desorption reaches zero.

Reaction rates of Type I are encountered when catalysts are poisoned.

In Type II the initial rate increases linearly with total pressure, $r_o = a\pi$. This situation applies when the adsorption of reactant A (or B) is rate-controlling where the other reactant B (or A) is not adsorbed or not present as in a unimolecular reaction. This type also holds for the uncatalyzed unimolecular reactions $A \rightleftarrows$.

In Type III the initial reaction rate can be expressed by the relations

$$r_o = \frac{a\pi}{1 + b\pi} \quad \text{or} \quad r_o = \frac{a\pi}{1 + b\sqrt{\pi} + c\pi}$$

TABLE 3. REPLACEMENTS IN THE GENERAL ADSORPTION TERMS.

$$\left[1 + K_A a_A + K_B a_B + K_R a_R + K_S a_S + K_I a_I\right]^n$$

Reaction	$A \rightleftarrows R$	$A \rightleftarrows R+S$	$A+B \rightleftarrows R$	$A+B \rightleftarrows R+S$
Where adsorption of A is rate controlling replace $K_A a_A$ by	$\frac{K_A a_R}{K}$	$\frac{K_A a_R a_S}{K}$	$\frac{K_A a_R}{K a_B}$	$\frac{K_A a_R a_S}{K a_B}$
Where desorption of B is rate controlling replace $K_B a_B$ by	0	0	$\frac{K_B a_R}{K a_A}$	$\frac{K_B a_R a_S}{K a_A}$
Where desorption of R is rate controlling replace $K_R a_R$ by	$KK_R a_A$	$KK_h \frac{f_A}{a_S}$	$KK_R a_A a_B$	$KK_R \frac{a_A a_B}{a_A}$
Where adsorption of A is rate controlling with dissociation of A replace $K_A a_A$ by	$\sqrt{\frac{K_A a_R}{K}}$	$\sqrt{\frac{K_A a_R a_S}{K}}$	$\sqrt{\frac{K_A a_R}{K a_B}}$	$\sqrt{\frac{K_A a_R a_S}{K a_B}}$
Where equilibrium adsorption of A takes place with dissociation of A replace $K_A a_A$ by	$\sqrt{K_A a_A}$	$\sqrt{K_A a_A}$	$\sqrt{K_A a_A}$	$\sqrt{K_A a_A}$
and similarly for other components adsorbed with dissociation.				
Where A is not adsorbed replace $K_A a_A$ by	0	0	0	0
and similarly for other components which are not adsorbed.				

In this type the rate increases with pressure to a maximum asymptotic value. This type is encountered where adsorption of either A or B is controlling in a bimolecular reaction $A + B \rightleftarrows$; also where surface reaction is rate-controlling in a unimolecular reaction $A \rightleftarrows$ with or without dissociation; and where desorption of R is controlling for finite values of the equilibrium constant K in a forward bimolecular reaction $A + B \rightleftarrows R$.

In Type IV,

$$r_o = \frac{a\pi}{1 + b\pi + c\pi^2}$$

the reaction rate starts off linearly with pressure, reaches a maximum value and then diminishes with further increase in total pressure to a constant asymptotic value. This type is characteristic of $A \rightleftarrows R + S$ where the surface reaction is rate-controlling and is also encountered in the reaction $A + B \rightleftarrows R + S$ where adsorption of A is controlling and proceeds with dissociation on dual sites.

In Type V,

$$r_o = \frac{a\pi}{1 + b\sqrt{\pi}}$$

the rate increases progressively with pressure, starting off linearly and approaches a value proportional to the square root of pressure. This type applies to the reaction $A + B \rightleftarrows$ where adsorption of B is rate-controlling and A is adsorbed with dissociation.

In Type VI,

$$r_o = \frac{a\pi^2}{1 + b\pi} \text{ and } r_o = \frac{a\pi^2}{1 + b\sqrt{\pi} + c\pi}$$

the rate starts off as the square of the pressure and approaches a rate proportional to the first power of pressure.

TABLE 4. EXPONENTS OF ADSORPTION TERMS

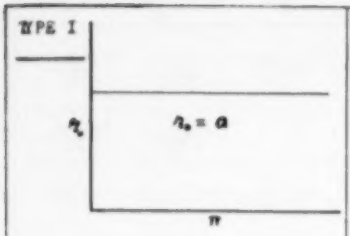
Adsorption of A controlling without dissociation	n = 1
Desorption of R controlling	n = 1
Adsorption of A controlling with dissociation	n = 2
Impact of A without dissociation $A + B \rightleftarrows R$	n = 1
Impact of A without dissociation $A+B \rightleftarrows R+S$	n = 2
Homogeneous reaction	n = 0

Surface Reaction Controlling	$A \rightleftarrows R$	$A \rightleftarrows R+S$	$A+B \rightleftarrows R$	$A+B \rightleftarrows R+S$
No dissociation of A	1	2	2	2
Dissociation of A	2	2	3	3
Dissociation of A (B not adsorbed)	2	2	2	2
No dissociation of A (B not adsorbed)	1	2	1	2

TABLE 5. INITIAL REACTION RATES OF SIMPLE GASEOUS REACTIONS.

Effects of Total Pressure.

TYPE I



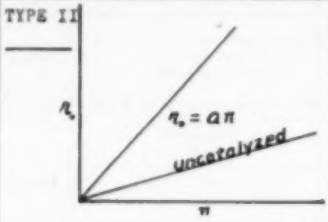
Desorption of One Product Controlling ($K \to \infty$)

Reaction	I	II	III	IV
Mechanism	c	c	c	c
	g	g	g	g
	j	j	j	j
	m	m	m	m
	-	-	P	P

Desorption of One Product Controlling ($K \to \infty$)
Equilibrium adsorption for S)

Reaction	I	II	III	IV
Mechanism		c		c
		g		g
		j		j
		m		m
				p

TYPE II

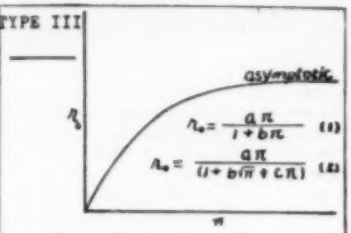


Adsorption of one reactant A (or B) Controlling where other reactant B (or A) is not adsorbed or not present

Uncatalyzed Reaction ($A \rightleftarrows$)

Reaction	I	II	III	IV
Mechanism	a	a		
	e	e		
	i	i	i	i
	l	l	l	l
			q	n

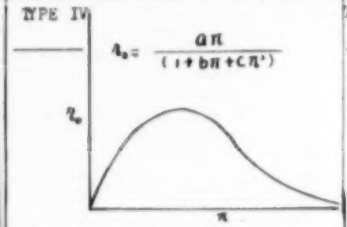
TYPE III



Adsorption of A controlling ($A \cdot B \rightleftarrows$)
Adsorption of B controlling ($A \cdot B \rightleftarrows$)
Surface reaction controlling ($A \rightleftarrows R$)
Surface reaction controlling ($A_2 \rightleftarrows$)
Desorption of one Product Controlling ($K \to \infty$)

Reaction	I	II	III	IV	Eq
Mechanism			a	b	(1)
			a	b	(1)
					(1)
	d				(1)
					(2)
	h	h			(2)
					(1)
	k				(1)
				o	(2)
	n				(2)

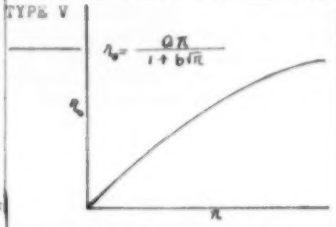
TYPE IV



Surface Reaction Controlling ($A \rightleftarrows R \cdot S$)
Adsorption of A controlling with dissociation ($A \cdot B \rightleftarrows R \cdot S$)

Reaction	I	II	III	IV
Mechanism		d		
			e	e
		k		

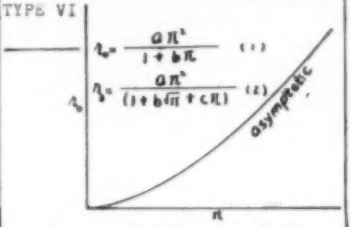
TYPE V



Adsorption of B controlling with dissociation of A ($A \cdot B \rightleftarrows$)

Reaction	I	II	III	IV
Mechanism			f	f

TYPE VI



Surface reaction controlling (B not adsorbed) ($A \cdot B \rightleftarrows R$)
Impact of A controlling (A not adsorbed) ($A \cdot B \rightleftarrows R$)
Surface reaction controlling (A dissociated, B not adsorbed) ($A \cdot B \rightleftarrows$)

Reaction	I	II	III	IV	Eq
Mechanism			k		1
			o		2
			n	n	1

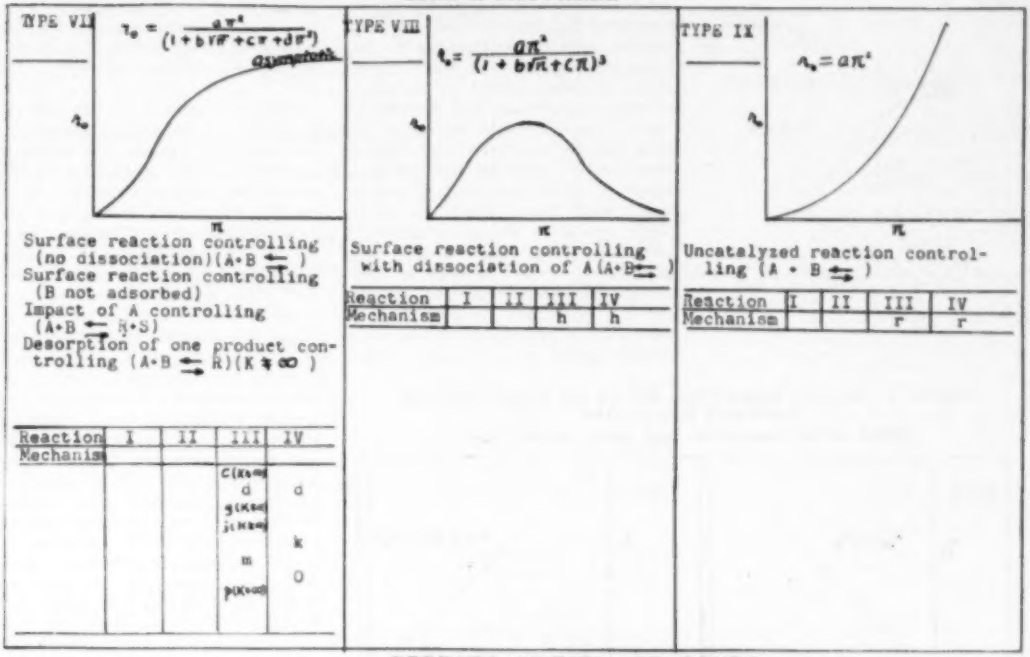
This type is manifest when the surface reaction is controlling for the reaction $A + B \rightleftarrows K$ where B is not adsorbed; and for reaction $A + B \rightleftarrows$ where the surface reaction is rate-controlling with A dissociated upon adsorption and with B not adsorbed. It also holds for the reaction $A + B \rightleftarrows K$ where A is not adsorbed and the controlling step is the impact of A upon reactant B which is held on the catalyst surface by chemisorption on a single site.

Type VII.

$$r_o = \frac{a\pi^2}{1 + b\sqrt{\pi} + c\pi + d\pi^2}$$

is a common type where the reaction starts out as the square of the pressure and then falls off in slope to a zero value reaching a rate of constant asymptotic value. This case is typified by four cases, (1) by the reaction $A + B \rightleftarrows$ where the surface reaction is controlling and which proceeds without atomic dissociation; (2) for a surface reaction controlling without adsorption of B; (3) in the reaction $A + B \rightleftarrows R + S$ where impact of A is controlling or (4) where desorption of product R is controlling for the reaction $A + B \rightleftarrows K$ and for finite values of K.

TABLE 5. (Continued)
Effects of Total Pressure.



EFFECTS OF TOTAL PRESSURE

In Type VIII,

$$r_o = \frac{a\pi^2}{(1 + b\sqrt{\pi} + c\pi)^3}$$

the rate initially increases as the square of pressure, the slope then falls off to zero at a maximum rate and becomes negative with further increase in pressure. This type applies where surface reaction is rate controlling with dissociation of A in the reaction $A + B \rightleftarrows$.

Type IX, $r_o = a\pi^2$, represents the behavior of the uncatalyzed bimolecular reaction $A + B \rightleftarrows$ where the rate increases progressively with the square of pressure.

Effect of Feed Composition upon Initial Rates. The effect of feed composition in a bimolecular reaction upon the rate of disappearance of the limiting reactant A falls into six types of rate curves, as shown in Table 6, assuming only one rate-controlling step.

In Type I, $r_{Ao} = aN_A$, the rate increases linearly with the mole fraction of A. This type holds where adsorption of A is the controlling step when B is not adsorbed. The extrapolation of the straight line to $N_A = 1.0$ means that the adsorption rate for A is fastest when there is no B present. However, if there is no B present there is no over-all reaction, the catalyst soon becomes saturated with A, and adsorption stops. This situation indicates that when the mole fraction of A approaches unity the rate of reaction must be less than the instantaneous rate of adsorption and hence some other mechanism must also be controlling such as the surface reaction or the impact of B upon the adsorbed A. This difficulty can be eliminated by applying adsorption as a rate-controlling step only to the limiting reactant.

In Type II, $r_{Ao} = a(1 - N_A)$, the rate of adsorption of B is controlling where A is not adsorbed. Extrapolation to $N_A = 0$ gives a maximum value corresponding to the rate of adsorption of B in the absence of A. Under this circumstance there is no over-all reaction. The same anomalous situation is encountered as in Type I.

In Type III,

$$r_{Ao} = \frac{aN_A}{1 - bN_A} \quad \text{or} \quad r_o = \frac{aN_A}{(1 - bN_A)^2}$$

the rate curve increases more than linearly with the mole fraction of A and is represented by the adsorption of A controlling with or without dissociation where B attains equilibrium adsorption. The same situation at $N_A = 1.0$ is encountered as in Type I.

In Type IV,

$$r_{Ao} = \frac{a(1 - N_A)}{1 - bN_A} \quad \text{or} \quad \frac{a(1 - N_A)}{1 + b\sqrt{N_A}}$$

the situation corresponds to the adsorption of B as controlling with or without dissociation, when A is at equilibrium adsorption.

In Type V, $r_{Ao} = a$, the rate is independent of feed composition. This means that the desorption of product R is controlling when K is infinite for the reaction $A + B \rightleftarrows R$. In the extreme ranges of gas composition in the absence of either reactant no product can be formed and hence the rate represents desorption and not reaction. At low concentrations of either A or B desorption of R no longer remains the only rate-controlling step.

In Type VI the reaction rate is zero in the absence of either A or B and attains a maximum value near the middle of the composition range. For catalytic reactions this situation holds (1) for all cases where the surface reaction is controlling; (2) where desorption is controlling and K is finite for the reaction $A + B \rightarrow R$; and (3) where impact of an unabsorbed reactant is controlling. This situation also applies (4) to the homogeneous bimolecular gas reaction.

The following specific equations apply

to Type VI and are not shown in Table 6:

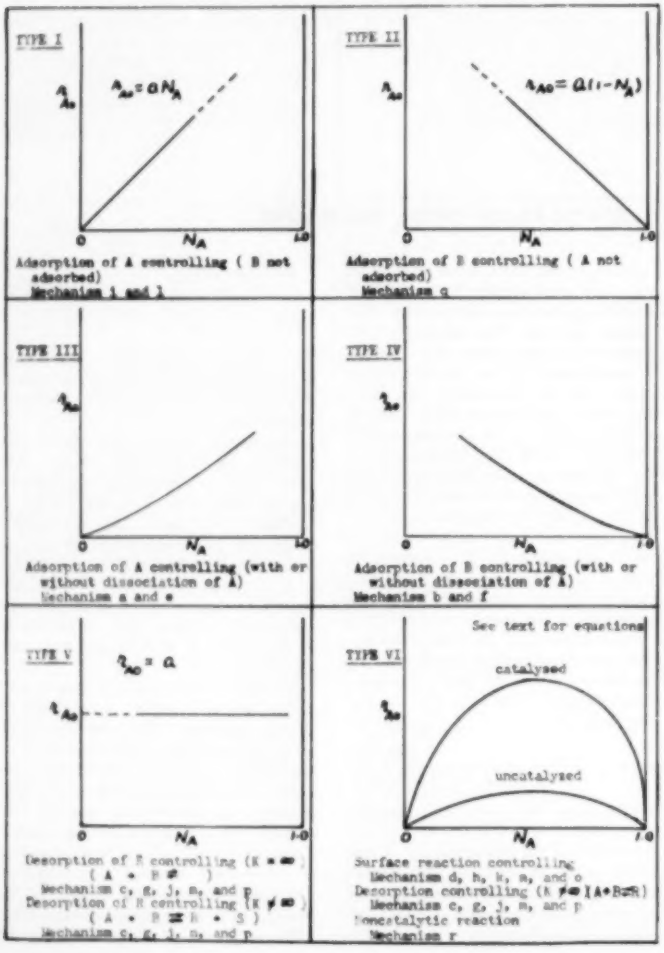
	Rate Controlling Mechanism III	IV
$r_a = \frac{aN_A(1-N_A)}{1 \pm bN_A - cN_A^2}$	c, p, j ($K = \infty$)	
$r_a = \frac{aN_A(1-N_A)}{1 + b\sqrt{N_A} + cN_A - N_A^2}$	c ($K = \infty$)	
$r_a = \frac{aN_A(1-N_A)}{(1 + b\sqrt{N_A} - cN_A)^2}$	q	b
$r_a = \frac{aN_A(1-N_A)}{(1 + b\sqrt{N_A})^2}$	n	n
$r_a = \frac{aN_A(1-N_A)}{(1 \pm bN_A)^2}$	d	d
$r_a = \frac{aN_A(1-N_A)}{1 \pm bN_A}$	k, o	k, o
$r_a = aN_A(1-N_A)$	r	r

Effect of Extent of Conversion Upon Catalytic Reaction Rates. To establish the mechanism of a catalytic reaction by a study of the effect of conversion upon reaction rates is too extensive for detailed examination in this paper. Curves shown in Tables 5 and 6 for the effects of total pressure and feed composition are for zero percentage conversion. To show the effects of conversion each of these curves would be replaced by a family of curves, one for each percentage. Each curve would be of a shape similar to the parent curve at zero conversion but would drop progressively with increase in percentage conversion and reach a zero rate curve at equilibrium. In general where adsorption is controlling, the rate curve plotted against conversion at constant pressure and temperature is concave downwards and where surface reaction is controlling is concave upwards (Fig. 11). For reversible reactions the same relative effects are observed but the falling off in rate is more marked.

Effect of Temperature. The effect of temperature is of minor importance in the selection of reaction mechanisms of catalytic reactions, contrary to popular notions, but is indispensable in establishing the entropies and enthalpies of formation of the activated complex and of the adsorption compounds of the catalyst with the various reactants and products. This anomalous situation is encountered even where the reverse reaction is negligible. Where adsorption or desorption are rate-controlling steps in irreversible catalytic reactions the rate is accelerated with increase in temperature whether the over-all reaction is exothermic or endothermic (Fig. 12). The same is true for the uncatalyzed irreversible reaction. However, where the surface reaction is rate-controlling the rate increases with temperature to a maximum value and then decreases, as shown by Tschernitz, Bornstein, Beckmann and Hougen (*5*). This reversal of rate is due to the unfavorable effect of temperature in removing the reactants from the surface which more than offsets the favorable effect of temperature upon the reaction velocity constant.

TABLE 6. INITIAL REACTION RATES OF BIMOLECULAR GASEOUS REACTIONS.

(Effect of feed composition upon initial reaction rates)


TYPE I
$r_{A_0} = aN_A$
Adsorption of A controlling (B not adsorbed)
Mechanism i and l
TYPE II
$r_{A_0} = a(1-N_A)$
Adsorption of B controlling (A not adsorbed)
Mechanism q
TYPE III
Adsorption of A controlling (with or without dissociation of A)
Mechanism a and e
TYPE IV
Adsorption of B controlling (with or without dissociation of A)
Mechanism b and f
TYPE V
$r_{A_0} = a$
Desorption of R controlling (K = ∞ (A + B ≠) Mechanism c, g, j, m, and p
Desorption of R controlling (K ≠ ∞ (A + B ⇌ R + S) Mechanism c, g, j, m, and p
TYPE VI
See text for equations
catalyzed
uncatalyzed
Surface reaction controlling Mechanism d, h, k, m, and o
Desorption controlling (K ≠ ∞ (A+B⇌R) Mechanism c, g, j, m, and p
Noncatalytic reaction Mechanism r

Summary

In this paper a survey is given of the general procedures in planning and correlating experimental data on gaseous reactions catalyzed by solids. Methods are given for eliminating, minimizing, or evaluating the temperature and concentration gradients in gas films and in catalyst pellets. A summarized procedure is given for setting up the rate equations for many postulated mechanisms of four simple molecular reactions, $A \rightleftarrows R$; $A \rightleftarrows R + S$; $A + B \rightleftarrows R$; and $A + B \rightleftarrows R + S$. The selection of reaction mechanism from the effects of pressure, feed composition, and extent conversion and temperature is given, especially with reference to the visual appearance of rate curves. After the mechanism of a reaction has been established the various constants in the appropriate rate equations can be obtained from the experimental data by graphical and statistical methods. These methods are not presented in this paper, but are given in (*5*).

It is recognized that there are shortcomings to the equations presented in this paper, that chemical reactions are not as simple as these imply, that several steps may be rate-controlling, that the adsorption equilibrium constants may be

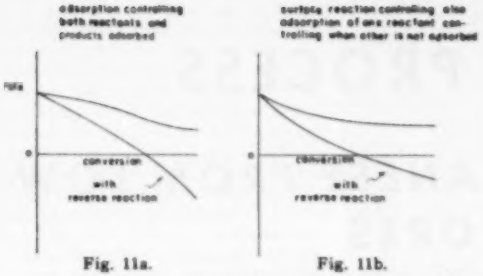


Fig. 11a. Fig. 11b.

Fig. 11. Effect of Extent Conversion Upon Catalytic Reaction Rates.

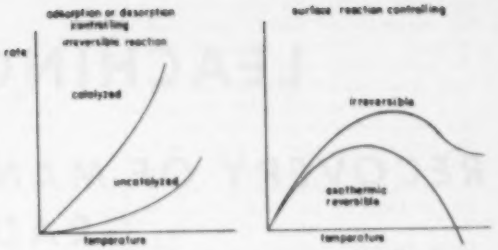


Fig 12a. Fig. 12b.

Fig. 12. Effect of Temperature Upon Catalytic Reaction Rates.

pressure-dependent as well as temperature-dependent. The present approach represents an attempt to compromise between methods which are so involved in theory as to be beyond the experiences and training of those entrusted to process design, and methods which are so empirical as to be unsafe for extrapolation beyond the range of experimentation.

Acknowledgment

Credit is herewith given the Wisconsin Alumni Research Foundation for the support of this project.

Notation

A = component A
a = activity
a_A, a_B, a_R, a_S, a_I = activities of components A, B, R, S, I, respectively
a_p = surface area per single catalyst pellet
a_m = surface area of pellets per unit mass
a = constant
b = constant
B = component B
C_p = specific heat
c = constant
D = diameter
D_{Am} = mean diffusivity of component A in a gas mixture
D_p = effective particle diameter equal to diameter of a sphere having the same surface area as the particle
D_p' = effective particle diameter equal to diameter of a sphere having the same volume as particle
E = effectiveness factor
F = feed rate, moles per unit time
F_e = external void fraction
F_i = internal void fraction
G = mass velocity
ΔH = heat of reaction
h_G = heat transfer coefficient of gas film
I = inert gas
j_d = factor for mass transfer
j_h = factor for heat transfer
K = over-all equilibrium constant
K_A, K_B, K_R, K_S, K_I = adsorption equilibrium constants for components A, B, R, S, I, respectively
k = thermal conductivity
k_G = mass transfer coefficient of gas film
k = reaction velocity constant for the homogeneous reaction
k_A = reaction velocity constant where adsorption of A is controlling
k_B = reaction velocity constant where adsorption of B is controlling
k_R = reaction velocity constant where desorption of R is controlling
k_s = reaction velocity constant where surface reaction is controlling
M_m = mean molecular weight
m = modulus
N_A = mole fraction of component A
n = constant
p = partial pressure
p_f = pressure factor
p_A, p_B, p_R, p_S, p_I = partial pressures of components A, B, R, S, I, respectively
q = rate of heat transmission
r = rate of reaction, moles per unit mass of catalyst
r_o = initial rate of reaction, moles per unit mass of catalyst
R = component R
S = component S
T = temperature, absolute
t = temperature
W = mass of catalyst

$$X = \left(\frac{\sqrt{a_p r M_m \rho_f}}{p_A \mu a_m}\right)\left(\frac{\mu}{\rho D_{Am}}\right)_f^{2/3}$$

$$X' = \left(\frac{r\Delta H \sqrt{a_p}}{a_m \mu C_p T}\right)\left(\frac{C_p \mu}{k}\right)_f^{2/3}$$

X_A = fractional conversion of component A per mole of feed

Greek Letters:

α, α', α'' = constants
μ = viscosity
π = total pressure
ρ = density
ρ_B = density of bed
ρ_p = density of particle

Subscripts:

A, B, R, S, I = components A, B, R, S, I, respectively
f = gas film
G = gas film
i = interface
m = mean
m = mass
p = particle
s = surface
v = volume

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LEACHING PROCESS

RECOVERY OF MANGANESE FROM LOW-GRADE ORES

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ABOUT 600,000 tons of manganese, principally as ferromanganese, spiegeleisen and silicomanganese, is used annually in the United States in the manufacture of steel, both as a deoxidant and as an alloying element. Modern steels cannot be manufactured by known methods, except at greatly increased cost, without manganese, and this emphasizes its strategic importance in the national economy. Although this country possesses large reserves of low-grade manganese ores, deposits suitable for direct smelting to ferromanganese are very scanty. This paper describes a process for recovering manganese from low-grade ores by leaching with the waste pickle liquor which is produced in large volume in certain steel manufacturing operations.

As an alloying element, manganese imparts desirable physical properties to a wide range of commercial steels. Combined with a number of nonferrous metals it forms important alloys for specialized applications. Compounds of manganese, though the quantities consumed are relatively small, find diversified uses throughout the field of chemical technology.

Commercial deposits of manganese ores occur in thirty-five states. Their manganese content varies widely, ranging from 1 per cent to more than 50 per cent in a few cases. Certain of these ores yield concentrates of ferro grade by mechanical beneficiation, but most are too lean or too impure to justify treatment by the methods of the mining engineer. As a result, the bulk of the ore used industrially is imported from abroad, chiefly from Russia, India and Africa.

Since the oxide ores of manganese are by far the most important commercially, the principal minerals are pyrolusite, psilomelane, and manganite. The manganocalcites, of which there are immense deposits in South Dakota, can readily be sintered to oxides but the ore nodules are sparsely distributed in a clay matrix which makes recovery costly. Recovery of manganese from the rhodochrosite in these deposits has been practiced commercially on a limited scale.

In general, the extent to which manganese ores can be improved by ore dressing depends upon the degree of intimacy of admixture of the ore and its impurities. Chemically combined impurities can be eliminated only by pyro- or hydrometallurgy. Iron, the most common metallic impurity, is usually difficult to remove by ore-dressing, and its content determines the kind of alloy that can be made. Silica, alumina, lime, magnesia, and baryta form a slag in the smelting process and these must be held within limits for economical operation. A large slag volume increases coke consumption, and the slag always carries away some of the manganese. The phosphorus in an ore passes almost entirely into the ferro-alloy on smelting, and high-phosphorus ores cannot ordinarily be used. Sulfur is much less objectionable because it can be made to combine more or less completely with the slag.

Manganese forms a series of oxides whose basicity decreases as the valence of the manganese increases. The monoxide resembles calcium oxide in basicity, and the heptoxide is an acid anhydride with as strongly acidic properties as perchloric acid. The dioxide has weakly basic or acidic properties, depending on conditions. An appreciation of this range of basicity is essential to an understanding of the hydrometallurgy of manganese.

A great deal of research has been devoted to development of processes for utilizing low-grade manganese ores. Ore-dressing methods have been studied extensively by the U. S. Bureau of Mines (*5*). Hydrometallurgical processes have interested many workers, and a variety of solvents, including the chlorides and sulfates of a number of metals, sulfuric, hydrochloric, and nitric acids, chlorine, ammonium sulfate and chloride, and sulfur dioxide is reported in the literature. Only the Bradley (*1*) ammonium sulfate and the Leaver (*2*) sulfur dioxide processes have attracted wide attention. The U. S. Bureau of Mines has been investigating the electrowinning of manganese since 1936 (*4*), and a process yielding manganese metal 99.9+ per cent pure has been operated on a pilot scale (*3*). It is reported that there are some commercial operations of the electrolytic process.

Leaching with Waste Pickle Liquor

A consideration of the chemistry of manganese discloses that a common chemical, ferrous sulfate, could be used to win manganese from its ores. Ferrous sulfate has the chemical properties both of strong reducing agents and strong acids, and this combination affords a made-to-order reagent for the purpose. The compound is available in large quantities in every steel-making district as a component of pickling liquor, a waste material from the essential operation of removing oxide scale from certain steel products by immersing them in dilute sulfuric acid. Composition of waste pickle liquor will usually fall in the range 0.5 to 10% sulfuric acid, and 10 to 22% ferrous sulfate, by weight. It has been estimated that a minimum of 600,000,000 gal. of this liquor, with an average weight of 10 lb./gal., is produced an-

nually in the United States. Additional large quantities are produced in other industries, notably, in the manufacture of titanium dioxide.

Commercial acceptance of a process based on pickle liquor would not only provide means for recovering manganese from low-grade ores, but also would present a method for solving a difficult waste disposal problem. Pickle liquor cannot be discharged to streams because of its pollutional effects. It is not acceptable in substantial concentrations in municipal sewer systems because of its corrosiveness and its interferences with sewage treatment processes. Many methods have been suggested for utilizing it economically, but up to the present time none has been successful in practice. As a result, it must be neutralized or stored in lagoons, and either of these expedients is both costly and wasteful.

Proposed Process

The foregoing situation provided the basis for the development of a process for producing an oxide concentrate low in impurities and containing upwards of 60% manganese. The process will yield pure manganese sulfate or chloride where these are the preferred manganese compounds. No liquid waste is produced, and a secondary pollution problem thereby is avoided.

Production of the oxide concentrate involves four principal operations: (1) Ground ore is leached with pickle liquor, and the sulfate solution is separated from the gangue; (2) the sulfate is converted to a chloride solution by treatment with calcium chloride, and the precipitated calcium sulfate is filtered off; (3) the optimum proportion of iron is separated from the pregnant solution by differential precipitation with chalk or pulverized high-calcium limestone; (4) manganese is precipitated from the solution with high-calcium lime slurry. The precipitate is filtered off, washed and dried as product, and the calcium-chloride solution remaining is concentrated for reuse.

Ore Leaching. Three mineralogically different oxide ores, with manganese contents ranging from 14.7 to 26.9% were used in studying the leaching reaction. When ores were leached with a pickle liquor of appropriate composition the dissolution of manganese was quite rapid, and particle size was found to be a significant variable, but not a critical one. Figure 1 illustrates the efficiency of leaching manganese from a 15% ore. These results were obtained by simple agitation of ore and liquor; pebble-milling converted the precipitated ferric hydrate to a semicolloidal material difficult to separate from the extract, and did not increase leaching efficiency.

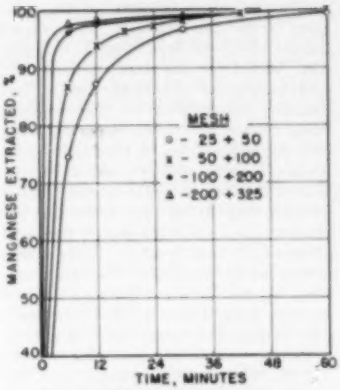

Fig. 1. Efficiency of Leaching Manganese from 15% Ore.

Results of leaching studies established the important fact that grinding finer than −100 +200 mesh is not essential for complete extraction. Grinding ores to about 60-mesh is a relatively low-cost operation, but, as grinding is carried to finer and finer mesh sizes, the cost rises rapidly. Since 98% of the manganese can be extracted from 60-mesh ore in only 30 min., finer grinding would not appear to be justified.

The effect of temperature on extraction rate was not studied systematically, but, as might be expected, the rate of reaction increases with temperature. Detailed study of this variable was not undertaken because of the rapid rate of reaction at room temperature. Where it is desirable to increase the reaction rate by raising the temperature, the higher temperature can be attained without supplemental heat by using the pickle liquor promptly after it is discharged from the picklers, where its temperature is 180° to 220° F.

Before the optimum ratio of ore to pickle liquor could be established, it was necessary to investigate the chemical reaction involved. Chemical analysis showed that practically all the manganese in each of the ores was present as the dioxide, and it was first assumed that the extraction would proceed according to the textbook equation

$$MnO_2 + 2FeSO_4 + 2H_2SO_4 = MnSO_4 + Fe_2(SO_4)_3 + 2H_2O \quad (1)$$

and leach liquor concentrations were adjusted to provide the stoichiometric amounts of ferrous sulfate and sulfuric acid indicated. This resulted in substantially complete extraction, but physical properties of the gangue material varied among the three ores and it was found that leach liquor composition affected the filterability of the gangue. This led to the discovery that good extractions could be obtained with large deficiencies of both ferrous sulfate and sulfuric acid, as measured by Equation (1), and that fairly good (84%) extractions could be obtained with solutions of ferrous sulfate alone.

The extracts all contained ferric sulfate as well as manganous sulfate, and it was recognized that the merit of the process could be enhanced if the formation of ferric sulfate could be prevented. Elimination of the ferric sulfate in the leaching operation would avoid the necessity for later separating it from the extract liquor. This could be accomplished by reducing the dioxide in the ore to the sesquioxide, which is reported to react with ferrous sulfate according to the equation

$$Mn_2O_3 + 2FeSO_4 + 3H_2O = 2MnSO_4 + 2Fe(OH)_3 \quad (2)$$

If the reaction followed this equation it would possess the additional advantage of extracting twice as much manganese per unit volume of leach liquor as the reaction assumed for the first trial extractions. Manganese dioxide can be easily reduced to the sesquioxide by roasting in a neutral or a reducing atmosphere at a relatively low temperature (250° C.) for a short time (15 min.).

Ores were roasted in a small rotary kiln, but accurate temperature control could not be attained and it was difficult to produce a calcine in which all the manganese was present as the sesquioxide. Chemical evidence indicates, however, that manganese sesquioxide reacts as if it had the composition $MnO \cdot MnO_2$, and, in practice, ores were slightly overreduced and blended with enough native ore to yield an oxide composition with a MnO/MnO_2 ratio of unity.

Ore samples simulating the sesquioxide were extracted with leach liquor based on Equation (2). Extraction efficiencies were uniformly lower than with native ore, averaging less than 90%, and ferric sulfate, though reduced in concentration, was present in the extracts in considerable amounts. A variety of leach liquor compositions showed that a small excess (5% to 10%) of ferrous sulfate, and a small amount of free sulfuric acid (0.04 g. H_2SO_4/g. $FeSO_4$) increased extraction efficiency and improved slurry filterability.

Investigation of the extraction step demonstrated that the assumed equations did not represent the leaching reaction for either the dioxide or the sesquioxide. An explanation of the anomalous results that were obtained when the textbook reactions were applied to this operation lies in the fact that fer-

rous sulfate can act both as a strong acid and as a powerful reducing agent. It has been pointed out that manganese monoxide is a strong base, and, as ferrous sulfate can act as a strong acid, these two compounds will react in a fashion analogous to the reaction between the monoxide and sulfuric acid, thus

$$MnO + H_2SO_4 = MnSO_4 + H_2O \quad (3)$$

$$MnO + FeSO_4 + H_2O = MnSO_4 + Fe(OH)_2 \quad (4)$$

Also, since ferrous sulfate can act in a dual capacity, it can provide the acid as well as the reducing power required in the manganese dioxide reaction. In addition, ferric iron has a strong tendency to form basic sulfates, and this tendency increases with the concentration of the reactants. A consideration of these facts suggested the hypothetical reaction,

$$MnO_2 + 2FeSO_4 + 2H_2O = MnSO_4 + Fe(OH)SO_4 + Fe(OH)_2 \quad (5)$$

Similarly, for the sesquioxide,

$$MnO \cdot MnO_2 + 3FeSO_4 + 3H_2O = 2MnSO_4 + Fe(OH)SO_4 + Fe(OH)_3 + Fe(OH)_2 \quad (6)$$

These equations show why it was possible to obtain fairly good extractions with ferrous sulfate alone. They show also that where ferrous sulfate was calculated on a manganese basis, the extractions were not complete without a small supplement of free acid because of the removal of sulfate ions from solution to form basic ferric sulfate. Conversely, they show why good extractions were obtained with large apparent deficiencies of free sulfuric acid. By the same reasoning, the observation that a small amount of free acid apparently was necessary for the complete extraction of the sesquioxide is explained by these equations.

The reactions that actually occur are undoubtedly more complex than might be assumed from the simplified equations already given. For example, the amounts of basic ferric sulfate and ferric hydrate that form will depend on the concentration of free sulfuric acid, and a small amount of free acid would prevent the formation of ferrous hydrate. The whole leaching reaction involves a complicated group of reactions, all seeking conditions of equilibrium, but the equations given serve to explain the anomalous results obtained when calculations were made on the basis of the textbook reactions, which obviously do not apply.

Physical characteristics of the residues from the leaching step varied among the three ores studied, and they also varied as the concentration and composition of the leach liquor was changed. Separation of the residues from the extracts is an important step, and the composition of the leach liquor should be adjusted to yield a residue that will filter or settle at the highest possible rate. It has been found that the presence of a small amount of free acid improves the settlability and the filterability of the residues. This may very well be due to the solution of ferric hydrate formed as a result of the complex of reactions that occur. No general principles can be set down for achieving the desired result in every case, because of variations in the gangue material associated with different ores. For this reason, a series of trial extractions is recommended to establish the optimum leach liquor composition for any particular ore. In general, a leach liquor with the composition of an average waste pickle liquor (15% $FeSO_4$ and 5% free H_2SO_4, by weight) will effect relatively complete extraction of manganese from common low-grade ores, and will result in a residue that will settle fairly well.

Conversion of Sulfates to Chlorides. Where it is desired to recover manganese in a form adapted to the manufacture of ferromanganese, it is desirable that the product be substantially free from sulfur. It is not possible to precipitate manganese from a solution of its sulfate with a cheap alkaline material, e.g., lime, because the coprecipitated calcium sulfate would contaminate the product. This difficulty can be largely overcome by converting the sulfates in the solution to chlorides. It can be accomplished readily by treating the extract with a solution of calcium chloride. The calcium sulfate can be recovered as the dihydrate in a pure form by filtration. It is a by-product of low value whose principal commercial use is in the manufacture of gypsum plaster and wallboard.

Conversion of sulfates to chlorides does not eliminate sulfate contamination completely. Calcium sulfate is appreciably soluble (about 2 g./l. in distilled water), and its solubility is increased by the presence of hydrochloric acid produced by any sulfuric acid in the original extract, or by hydrolysis of ferric chloride.

This procedure, however, reduces the sulfur in the final product to a low value. Extractions were made with ferrous chloride solutions by making the sulfate conversion on the leach liquor. Results obtained were similar to those with the sulfate liquor, and either method is satisfactory.

Separation of Iron from Manganese. Where the objective of the process is the preparation of pure manganous sulfate (or chloride), complete separation of iron from the extract liquor is essential. Where the objective is the recovery of manganese oxides for manufacturing ferromanganese, the concentrate should contain not less than 50% manganese, and the manganese-iron ratio should not be less than 9:1. Complete separation of iron is not necessary in this case, but the degree of removal will be a function of removal cost vs. value of product. Premiums are paid for manganese contents in excess of the minimum specified for any grade.

It has been the major purpose of this investigation to provide a process that would be attractive to the steel industry, and, as chemical manufacturing per se is more or less foreign to that field, emphasis has been placed on the preparation of a product suitable for ferromanganese manufacture. Where a manganese extract contains iron, and this will usually be the case, separation of the iron as a relatively pure oxide would be advantageous for enrichment of blast furnace dust prior to sintering.

Several methods for making this separation were investigated, but differential precipitation of the iron proved to be effective and easy to control. Ferric iron can be precipitated completely at a pH of about 3.5; the actual value depends somewhat on the presence of other dissolved salts. Ferrous iron begins to precipitate at pH 5.5, and the higher the pH the more rapidly it can be oxidized to the ferric state by aeration. Manganese, on the other hand, does not ordinarily begin to precipitate until the pH is raised to about 8.5. This favorable combination of properties provided a sound means for separating iron from manganese in solution.

Separation of the iron from manganese ions in extracts will be more nearly complete if all the iron is in the ferric state. When an alkaline agent is added to a solution of ferric and manganous chlorides, some manganese generally will be precipitated with the iron even though the average pH of the mixture is well below the point at which manganese begins to precipitate. This phenomenon presumably results, even where thorough agitation is provided, from small localized areas of high pH; the effect is particularly noticeable where the alkaline material is relatively insoluble, e.g., lime or calcium carbonate. This circumstance emphasizes the necessity for precipitating most of the iron in the ferric state if excessive loss of manganese is to be avoided. Where a large proportion of the iron is in the ferrous state it will be apparent that, as the average pH of the mixture is in-

creased, localized areas of high pH will tend to precipitate increasing proportions of manganese. Also, the pH at which manganese begins to precipitate is lower than the pH at which ferrous iron can be completely precipitated. In practice, however, extractions can be made so that the concentration of ferrous iron in the extracts is low. Where much ferrous iron is present, it is desirable to aerate the mixture during the iron removal step to oxidize the ferrous iron to ferric, and thus permit the operation to be performed at the lowest possible pH. Although any manganous hydroxide precipitated through localized increase in pH should redissolve when the pH is again lowered, it does not do so because it oxidizes rapidly to an insoluble compound, such as MnO·OH.

Development of this step in the process disclosed that slaked lime slurry was unsatisfactory as a precipitant because of its tendency to precipitate excessive amounts of manganese. Despite vigorous agitation it was impossible to disperse the lime slurry rapidly enough to prevent local increases of the pH above the manganese precipitation point. Precipitated chalk, however, served the purpose very well because it cannot, of itself, raise the pH much above 8. By adding the chalk slowly and providing rapid agitation, 98% of the iron, and no more than 5% of the manganese, can be precipitated if the average pH of the mixture is not allowed to rise above 4.2.

In distinction from the recovery of manganese oxide for ferromanganese manufacture, if manganese sulfate, or chloride, is the desired product the iron must be completely removed from solution before crystallization of the salt. Manganese sulfate can be prepared in a state of high purity by treating the clear extract from the gangue filter with sufficient calcium carbonate, as just described. Manganous chloride can be similarly prepared by precipitating the iron from the filtrate from the chloride conversion step. The relatively high value of these salts permits a substantial loss of manganese in the iron removal operation without significantly affecting the economics of the process. If an appreciable amount of manganese were precipitated with the iron hydrate, it could be recovered by recycling the precipitate.

Production of Oxide Concentrate. Manganese concentrates intended for the manufacture of ferromanganese should contain the highest possible proportion of manganese. This means, in effect, that manganese monoxide should be the predominant compound in the concentrate, because it contains the highest percentage of manganese of any of the oxides of that element.

The purified extract is principally a solution of manganous and calcium chlorides. The manganese is precipitated as a hydrated oxide by adding high-calcium lime slurry until the pH of the mixture rises to 9.5. During the precipitation it is desirable to exclude air, as far as possible, to avoid oxidation of the monoxide to dioxide, thereby diluting the concentrate with oxygen. Concentrates produced in this manner filter readily. The filtrate, which is essentially a solution of calcium chloride, is concentrated by evaporation for reuse in the chloride conversion step.

A typical product from the process, starting with a 16% ore, contained 60.9% manganese. Roasting the product for an hour at a dull red heat raised its manganese content to 64.5%. An analysis of the unroasted product is given in Table 1.

Flow Sheet. A schematic flow sheet is shown in Figure 2. Countercurrent stage decantation is indicated as a means for recovering values from the gangue, because a procedure of this general nature was used in developing the process. Slurries from the leaching operation are sometimes difficult to settle and filter. These properties can usually be improved by pH adjustment, and a continuous decanter and sludge thickener would handle most slurries satisfactorily in practice. The method indicated for washing the other precipitates would be practical because these materials can be filtered and washed without difficulty.

In illustration of the approximate size of the equipment for a commercial installation of the process, a design data sheet is shown in Figure 3. Conversion of 48 tons of 15% ore/24 hr. was chosen for the design, since that quantity would require about 75,000 gal. of pickle liquor of average composition, and a number of the larger steel mills produces this daily volume of potential leach liquor. The equipment has been figured from conservative estimates of capacities, particularly for the four filtrations, where 20, 100, 25 and 50 lb. of dry solids/sq.ft. of filter area/hr. have been assumed for filtration of gangue, calcium sulfate, iron hydrate, and manganese concentrate, respectively. The possibility that one or another of the various salts might crystallize and clog the equipment was taken into consideration; solubility relationships showed that no difficulty would arise from this cause.

TABLE 1.—ANALYSIS OF MANGANESE CONCENTRATE, %

Manganese as MnO_2	34.04
Manganese as MnO	30.20
Iron as Fe_2O_3	2.33
Calcium as CaO	0.62
Magnesium as MgO	0.45
Silica	1.84
Phosphorus	nil
Sulfur as SO_3	1.80
Moisture at 120° C.	3.82

The process has been designed to operate partly continuously and partly on the batch basis. As noted in the figure, duplicate reaction tanks were provided, to be charged alternately, on a one-hour cycle. Each tank would then discharge alternately to the respective filter, which would operate continuously. This is a flexible design that would permit adjustment of cycle time to reaction rate. Although the process probably could be operated wholly continuously, a confident design could be evolved only on the basis of further pilot studies. The design suggested has the merit of compactness, simplicity, and relatively low cost.

This process is covered by U. S. Patent 2,462,409, issued Feb. 22, 1949.

The basic principles involved in converting low-grade ores with waste pickle liquor have been established. Various ores behave in an individual fashion, and actual procedures must be modified to suit specific ores, but the fundamentals of the process as stated are such that they can easily be applied to any given situation.

Although the technology of the process is simple enough, the geographical distance of most commercial deposits of low-grade ore from sources of waste pickle liquor is an economic disadvantage. The increasing attention being given to production of ferrous sulfate monohydrate from pickle liquor may provide a solution to the problem of transportation economics. Monohydrate can be shipped a fairly long distance, and successful application of this compound to the process would permit the chemical operations to be carried out at the ore site where land is cheap. Laboratory studies are in progress to evaluate the effectiveness of monohydrate as a leaching agent.

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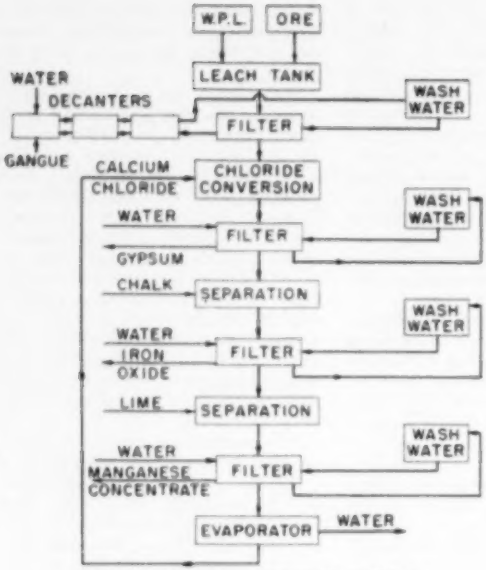


Fig. 2. Manganese Process Flow Sheet.

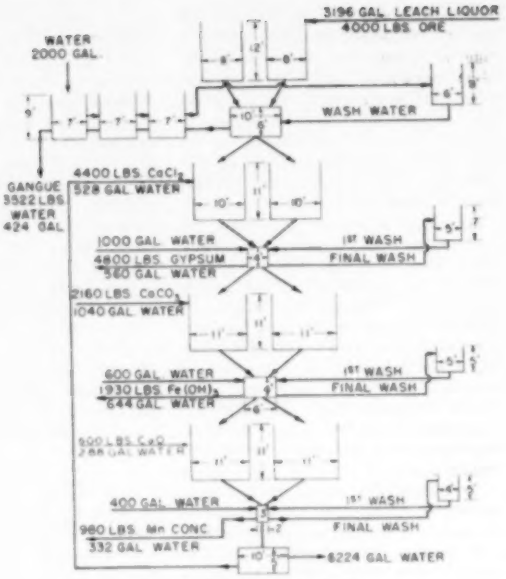


Fig. 3. Design Data Sheet.

Discussion

A. G. Lamont (Eldorado Mining & Refining Co., Port Hope, Ont.): About the filtration of iron cake—Do you have to boil the solution before the filtration or does it filter well enough for plant operation without boiling?

Also I notice only one outlet for impurities and that is in the iron cake. I was interested in the build-up of impurities of chloride liquor, whether this process has been run on a multicycle basis, and if so, if that build-up of impurities has caused trouble in any part of the process; also whether the build-up of impurities would affect production of purified materials such as manganese sulfate or chloride.

R. D. Hoak: We did not boil any of the suspensions in an attempt to improve filtration rate. We have found from experience that the iron precipitate filters fairly well if all the iron is in the ferric state. Similarly, a precipitate that is substantially all ferrous hydrate filters satisfactorily. But when a ferric precipitate contains a moderate amount of ferrous hydrate, the filtration rate is reduced considerably. This is also true when a ferrous precipitate contains much ferric hydrate. In general, our studies have shown that the methods given should be suitable commercially. It may be pointed out that the physical properties of the gangue suspension can be modified by pH adjustment.

On recycling the calcium chloride solution: Our work was done on a relatively small scale, with volumes of several gallons of solution, and it was not possible to make the kind of investigation required to reach a quantitative conclusion on the tendency of impurities to build up in the recycle. We studied the solubility relations of the compounds in the various solutions and did not anticipate an undue accumulation of contaminants in the chloride liquor. This is a question that should be investigated on pilot scale.

Anonymous: Dr. Hoak mentioned the problem of having the pickle liquor so far away from the source of the low-grade ore. It is my understanding that during World War I as well as the most recent one certain plants developed the use of tubes to smelters in close proximity to low-grade ore deposits. It is also my understanding that those plants have not proved to be economical during normal times. Is there some similar process which might prove to be economical?

R. D. Hoak: It is true that the Bureau of Mines has done considerable work with sulfur dioxide as a leaching agent. Attention has been drawn to the Leaver sulfur dioxide process, among others, and some rather extensive pilot studies were made. I don't know of any commercial operations of that type of process today. I should think that a smelter from which sulfur dioxide could be obtained in proximity to a deposit of low-grade ores would provide an economical process. The question of transporting pickle liquor has not been studied perhaps as carefully as it should be. There are many places in the United States where pickle liquor is being transported some distance. By that I mean a matter of 20 miles or more. It is being carried in ordinary steel tank cars or tank trucks. The possibility of hauling the material in suitable acid-resistant barges has been investigated, but here we found that rates for transporting pickle liquor have not been established.

Anonymous: Do you believe the sulfur dioxide process preferable if close to the mine source?

R. D. Hoak: That is a little difficult to answer. If smelter gases were available near a source of ore, the process should be economically sound. Our process was developed principally as a means for utilizing waste pickle liquor. How it would compare with an SO_2, or an ammonium sulfate process, I could not say without a knowledge of all local factors involved.

Anonymous: What happens to the phosphorus in the ore?

R. D. Hoak: We did not study phosphorus systematically. Our experimental ores contained about 0.2% phosphorus and the concentrates contained a trace, or none. I should guess that the phosphorus would be precipitated in the iron removal step. (*Note.* Since this discussion occurred, laboratory studies have shown that most of the phosphorus leached from the ore precipitates with the iron. A silicious ore containing 0.8% phosphorus yielded a concentrate containing 0.03%.)

(Presented at Twelfth Regional Meeting, Montreal, Canada.)

Yankee ingenuity and skill basis for industrial expansion of . . .

NEW ENGLAND

. . . Site of the A.I.Ch.E. Boston Regional Meeting

RALPH L. WENTWORTH

Massachusetts Institute of Technology, Cambridge, Massachusetts

MORE than three centuries of human activity have gone into the stage-setting for the Boston Regional Meeting of the Institute. This is the New England scene, and it offers a wealth of interest to those who will be attending the technical sessions of the meeting at the New Ocean House in Swampscott, Mass., May 28-31, 1950.

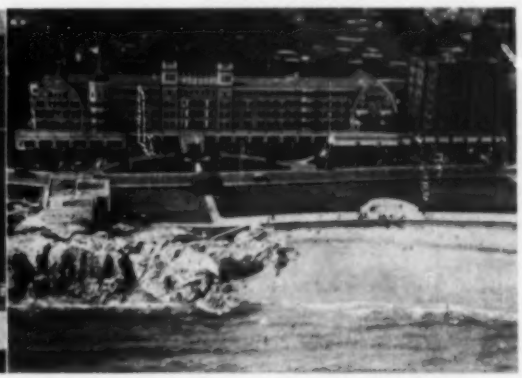
No other part of the United States is as neatly packaged as New England, containing an amazing diversity of industrial activity, vacation facilities, and historical interest. This diversity is the key to an understanding of New England. From the beginning, New Englanders have had a hand in a thousand varieties of enterprises, a fact that is underscored by the multitude of manufacturing and service industries making up the New England economy of today.

But the beginning came hard. The colonists who made the start had strong reasons for facing the job of carving a home and a living from the wilderness. These were men from all classes of

(*Continued on page* 16)

GENERAL COMMITTEE

MEETING SITE



Standing (left to right): J. Donovan, Vice-Chairman; R. Sutherland, Transportation; F. S. Carpenter (for A. Stokes), Hotels; J. B. Pohlenz, Plant Trips; N. A. Sargent, Treasurer; A. W. Fisher, Jr., Ways and Means; A. J. Good, Secretary; R. L. Geddes, Program; W. B. Parker, Jr., Hospitality; Seated (left to right); Mrs. C. P. Baker (for C. P. Baker), Registration; Mrs. J. J. Healy, Jr., Ladies' Committee; J. J. Healey, Jr., General Chairman; G. A. Randall, Printing; J. N. Addoms, Public Relations; W. C. Rousseau, Entertainment. At the right, bird's-eye view of New Ocean House, Swampscott, site of the Boston Regional Meeting.

NEW ENGLAND

(*Continued from page 15*)

English life, united in their religious beliefs and determined to live lives of their own direction. The story of the little band of Pilgrims that came ashore from the Mayflower at Plymouth in December, 1620, is one of the best known chapters in American history. If Plymouth had not offered a quiet harbor, an abundance of fish, and the opportunity of rifling the grain caches of the Indians, the story might well have ended very shortly. Fortunately, the Indians welcomed the colonists at their first meeting in the spring, and with this help the Plymouth Colony became a successful venture. By the end of the first decade this success had induced others to come over from England, and settlements were firmly established all along the New England coast.

First Chemical Engineer. Boston was given its name in 1630 and acquired its first chemical engineer in 1631 in the person of John Winthrop, Jr., who set about the establishment of salt-manufacturing, iron-making, and saltpeter extraction. Winthrop had a novel approach to the financing of his bold ventures, issuing stock in the modern Wall Street style at a time when European manufacturing was still hampered by the limited personal resources of the masters in the craft. The first technical paper ever read by an American was delivered before the Royal Society by Winthrop in 1662 and titled "Of the Manner of Making Tar and Pitch in New England."

This beginning of manufacturing, however tiny it seems today, was in response to a real need. The colonists were beset by the problems of establishing a self-sufficient community; for example, the loss of their homes by fire was a frequent occurrence simply because sources of lime for the construction of proper chimneys had not been located and exploited. Small industries helped to build the colonies into a collection of thriving communities. Prosperity became the colonists' lot, so much so that their booming trade in grain, furs, fish, oil, and lumber became real competition for the English merchants.

Seeds of Dissent. This background of business and trade, established so early in the history of New England, accounts for much of the friction that highlights the prerevolutionary relations between the mother country and the colonies. To be sure, there was a new spirit of freedom and self-determination in the colonists' approach to religion and government, but one of the chief reasons for the resistance of George III to this spirit was the loss of trade and tax revenue which was a certain consequence of self-determination. Until the Revolution, difficulties with the Crown were almost continuous, but New England was a going concern not to be hindered by a mere king's displeasure.

Alternating with their squabbles with the King were hostilities that began with the French in 1689 and continued intermittently until 1760. After victory was achieved, there followed promptly an attempt of George III to liquidate some of the heavy debt brought on by the war with the French by imposing the infamous Stamp Act upon the colonies. With the immediate and vociferous reaction to the Stamp Act began the march toward the Revolution. The Stamp Act was repealed, but only to be replaced by taxes on trade in tea, glass, paper, and other commodities. The Boston merchants retaliated with a boycott of a long list of British manufactures. When the Massachusetts Legislature refused to comply with a demand for the dissolution of the boycott, the Governor adjourned the Legislature and seven shiploads of British soldiers were sent to Boston. Friction between this garrison and the people of Boston culminated in the Boston Massacre in 1770.

Historic Battlegrounds. Parliament finally repealed all taxes except the one on tea, only to find that Boston would have its tea without a tax or not at all. To make certain that the point was well made, a rather odd-looking lot of Indians boarded the tea ships in Boston Harbor one December night and proceeded to stir a heady, if somewhat thin brew in the harbor. Parliament took her cup with exceedingly poor grace, ordered the port of Boston closed, and placed the city under martial law. This action was the signal for the formation of the military groups, calling themselves Minutemen. Their warlike preparation caused General Gage, commander of the Boston garrison, real concern, and it was an expedition of Gage's men to Concord bent on destroying military supplies gathered by the Minutemen that drew the "shot heard round the world," in a skirmish at Lexington.

General Gage's reaction to this declaration of war was a prompt withdrawal to Boston, which became a city under siege. While Gage fretted in Boston about his lack of troops and hoped that the colonists would see the error of their ways and reaffirm their loyalty to the King, every town and village cheered the patriots of Massachusetts. In June, 1775, General Washington was elected to command of the provincial troops that had assembled in Cambridge, and it was decided that Bunker Hill in Charlestown should be fortified. Gage met the challenge and, on attacking, carried the field with heavy losses.

Bunker Hill ended the shooting war for Boston; in 1776 Washington's men fortified Dorchester Heights under cover of a raw March night and forced the British to withdraw from the city. Although the fighting moved South, New England kept her share of the troubles that went with the waging of the war. Inflation, shortages and profiteering, Tories and an unwilling group of merchants and shippers whose business was ruined, played parts in hindering the prosecution of the Revolution. Patriotic zeal and stubbornness, the help of France and the inability of the British to win a decisive victory prevailed, however, and New England found itself, with the rest of the colonies, a free agent.

Industrial Awakening. New Englanders made good use of their freedom. With a new continent to be settled and the world to trade with, they set out to fill the demand. Shipping boomed, culminating in the great whaling fleets and clipper ships of the mid-nineteenth century. The mills were established; before the end of the century New England was supplying the country with nearly all finished cotton goods. This was the development of the industrial North. It became an arsenal for a nation at war with itself and supplied men and machines for the settling of the West. Intellectual accomplishments were not neglected. Proper schooling had been a prime consideration from the first, and the maturing economy did not neglect to add to the prestige of its educational system.

If the frontier had been limitless, this success story might have continued unabated. But New England found that her "fustest with the mostest" position began to wane as the country grew up. Competition increased while the center of gravity for markets and population moved westward. The lack of raw materials became a real handicap. With the aging of the twentieth century came evil days for many a New England industry. The loss of a large part of the textile industry laid many a town low. Business for many a venerable firm became as nothing compared to the booming earlier days. The inevitable result was a housecleaning.

Today's New England is successfully meeting tough competition. The comeback is compounded of a number of factors; perhaps the best summary of it is to say that Yankee ingenuity has won over Yankee intractability. A page-long list of manufacturers could be cited to show the diversification that is the back-

(*Continued on page 36*)

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PULP AND PAPER FOUNDATION

A Pulp and Paper Foundation at the University of Maine, to encourage fundamental research in the field was announced last month by officials of the university.

The Foundation according to the official announcement will foster a six-point program:

1. To interest students who major in chemical engineering or chemistry in the pulp and paper program.
2. To provide financial assistance in the form of loans and scholarships for students.
3. To offer a curriculum specializing in pulp and paper technology.
4. To screen students who have completed three or four years of basic college training, for a five-year course stressing operational management.
5. To augment the staff with personnel experienced in production management.
6. To advance fundamental and applied research for the pulp and paper and allied industries.

Dr. Arthur A. Hauck, president of the University of Maine, in making the announcement, stressed the part which industry will take in making the Foundation possible.

J. L. Ober, vice-president, Scott Paper Co., Chester, Pa., gave a detailed presentation of the need for the Foundation, its objectives and benefits. Pointing out that the pulp and paper industry must attract and develop more outstanding men with special training, Mr. Ober said the industry depends on two sources —in-the-plant and in-the-school training —for men for supervisory and management positions.

Strongly advocating university instruction, Mr. Ober explained that there are now 921 pulp and paper mills seeking the services of the approximately 120 students who are graduated each year from schools with pulp and paper curricula.

"This means that only one graduate is available right now for every seven mills," Mr. Ober declared.

DIAMOND UPS SILICATE OUTPUT

Diamond Alkali Co. recently put into operation a new, 50,000-ton furnace at its Cincinnati (Ohio) silicate plant. W. H. Evans, Diamond's general manager of silicate operations, said that the addition of the new furnace will increase production of silicate of soda and related products at the Cincinnati plant by 50 per cent.

The plant now will have three 50,000-ton furnaces. A new, gas-fired unit was installed in the furnace building, which was enlarged. Total cost of the expansion project was $300,000.

Production increases were attributed to the constantly growing demand in the oil industry for silica gel catalyst.

NEW FRACTIONATING TOWER PACKING

Pan American Refining Corp. has appointed The Marshall-Moorman Development Co., New York, N. Y., technical and licensing agents for Panapak, new industrial packing for fractionating towers.

A honeycomb-like assembly of multiple layers of expanded metal lath, Panapak, was invented by R. C. Scofield and patent rights are assigned to Pan American. It has been in use almost two years in a commercial installation at Pan American's oil refinery in Texas City, Tex., and Scofield described the packing to the A.I.Ch.E. at the Pittsburgh meeting. His paper, "Industrial Fractionating Tower Packing," will be published shortly in *Chemical Engineering Progress.*

BOOKLET AVAILABLE ON RADIOISOTOPES

A general survey of the tracer and control work being done with radioisotopes has been published by The Kellex Corp., 233 Broadway, New York, N. Y.

While directed primarily at the industrial reader, the pamphlet includes work on the life sciences.

In referring to the industrial employment of radioisotopes today, the company states that the uses range all the way from improving de-icers for aircraft to the development of new catalysts for petroleum refining.

In the petroleum industry tracers have been used in the laboratory to tag and follow hydrocarbons through various processes. A limited supply of booklets is available for distribution.

Also during the month in radioisotope work it was revealed by Dr. Charles E. Crompton of the Atomic Energy Commission, that 9000 shipments of radioactive materials have now been made by the Atomic Energy Commission to scientists in all parts of the country. More than 100 separate laboratories are now engaged in synthesizing radioactively labeled compounds.

Dr. Crompton revealed that the isotopes division of the AEC has contracted with six different laboratories for the development of practical methods of synthesizing 45 selected labeled compounds. The purpose of this program, he explained, is to make these compounds available at a price based only on the time and materials required to carry out the final synthesis. The division is now preparing a status report on chemically synthesized labeled compounds, he said.

Another important development in the application of tagged atoms to various research problems is the increasing number of scientists who are seeking and receiving training in the handling and use of radioisotopes. Last year alone, it is reported, the Oak Ridge Institute for Nuclear Studies trained about 400 scientists in the use of radioisotopes.

DOW BUILDING AMMONIA PLANT

The Dow Chemical Co. has begun construction on a new $5,000,000 ammonia plant at Freeport, Tex. The company states that it expects the plant to be completed by late 1950. The new plant will make available refrigeration grade and technical grade anhydrous ammonia in tank-car quantities as well as quantities of aqua ammonia to industrial and agricultural consumers in the South and the Mississippi Valley.

Anhydrous ammonia is a major source of nitrogen for use in fertilizers and has been used for direct fertilization in considerable quantity on the West Coast and in the Delta region of Arkansas, Louisiana, and Mississippi. Dow states that there are indications that this use will spread to the corn-growing regions of the Middle West and the cotton, rice, and vegetable sections of the South.

HOOKER TO EXPAND WEST COAST PLANT

E. R. Bartlett, president, Hooker Electrochemical Co., Niagara Falls, N. Y., has revealed plans for an increase in production facilities for caustic soda and liquid chlorine at the Tacoma (Wash.) plant. The work, which will be in charge of the company' own engineering staff, is expected to be completed in October.

Two circuits of old Type E electrolytic cells will be removed and replaced by Type S-3 cells. Additions for handling and treating brine, purifying caustic, and liquefying chlorine will also be made. Triple-effect pans will be used for caustic evaporation and a new boiler will supply additional steam requirements. Provision is to be made for additional rectifier capacity for converting alternating current to direct current required for the cells. The mercury rectifiers for this purpose are already on hand due to the purchase of a substan-

(*Continued on page 20*)

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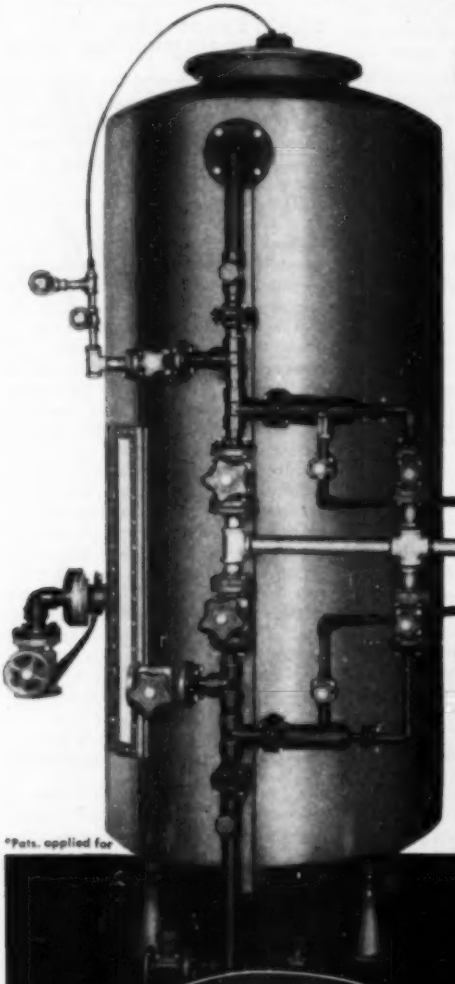

This newest development of ILLCO-WAY engineering and research provides a constant treated water—pH of 7±0.1—total dissolved solids (including CO_2 and silica) less than 0.1 ppm—with resistance over 10,000,000 ohms per cm (18°c).

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INDUSTRIAL NEWS

(*Continued from page* 18)

tial number from the War Assets Administration several years ago. Some of these are currently in use both at the Tacoma and the Niagara Falls plants. Other facilities will include a new cell construction and renewal building, additional storage tanks, water supply, expanded dock facilities, increased chlorine handling and liquefaction equipment, etc.

INSTRUMENTAL ANALYSIS OFFERED AT M.I.T.

Two one-week specialized training programs in instrumental analysis will be offered from July 10-14 and July 17-21 as part of the 1950 summer session at the Massachusetts Institute of Technology. In announcing the two courses, Prof. Walter H. Gale, director of the summer session, pointed to the greatly increased use of instrumental methods in applied analytical chemistry, particularly those involving optical and electrical instruments.

Dr. David N. Hume and Dr. Lockhart B. Rogers, both assistant professors of chemistry at MIT, will conduct the two courses.

The first week's program, from July 10 to 14, will be devoted to electrical methods of instrumental analysis and will emphasize potentiometry, polarography, conductimetry, amperometric titrations, and applications of self-balancing recording potentiometers.

Optical methods of instrumental analysis, including spectrophotometry, colorimetry, fluorimetry, nephelometry, and flame photometry, will be the subject of the second program, July 17 to 21.

Tuition for each one-week period will be $50. Application forms may be obtained from Professor Gale at Room 3-107, MIT, Cambridge 39.

FOSTER WHEELER HAS FRENCH SUBSIDIARY

Foster Wheeler Corp., New York, N. Y., has organized a French subsidiary, Societe Foster Wheeler Francaise, for handling European construction activities, according to H. S. Brown, chairman of the parent corporation. The French company will maintain offices at 6, Rond Point des Champs Elysees in Paris. R. M. Serre will direct the sales work on the Continent of Europe with headquarters at the Paris office.

E.C.P.D. ISSUES REPORT OF ACHIEVEMENTS

The Seventeenth Annual Report of the ECPD highlights the efforts being made to improve the competence of its members and to make engineering work more rewarding in personal satisfactions. A feature of this recently published report of 47 pages is an article, "What Is ECPD?" which relates the history, organization, and procedures of the ECPD, a conference organized in 1932 to enhance the professional status of the engineer through cooperative efforts of the eight engineering organizations among them the A.I.Ch.E.

Progress achieved during the past year (year ended Sept. 30, 1949) includes the following: Establishment of a 7-point program directed toward extension of educational processes into the period following graduation, and the Council's Canons of Ethics for Engineers.

Copies of the report can be obtained from ECPD, 29 West 39th Street, New York, N. Y., for 50 cents.

PROBLEMS WANTED

Stoichiometry, Kinetics, Unit Operations and other problems are wanted for the new edition of A.I.Ch.E. problems booklet. Actual industrial problems especially desired. Send problems and brief solution to Frank A. Anderson, Co-Chairman, Problems Committee, department of chemical engineering, University of Mississippi, University, Miss.

KELLOGG EQUILIBRIUM CHARTS AVAILABLE

Two large volumes of charts containing liquid-vapor equilibrium constants, and one large volume containing fugacities for light hydrocarbons in mixtures, have just been published by The M. W. Kellogg Co.

Samples of the charts, based on the Kellogg Equation of State, were first shown at the Pittsburgh annual meeting of the A.I.Ch.E. by Manson Benedict as part of his paper on liquid-vapor equilibrium. The charts have been checked by application to multicomponent experimental work performed in Kellogg laboratories and in various universities.

Differing from similar charts issued in the past, these Kellogg graphs are not only functions of temperature and pressure but also are a function of the composition of both the liquid and vapor phases. The charts cover pressures graduated from atmospheric to 1000 lb./sq.in.abs. for any mixture of hydrocarbons from methane to *n*-heptane, including unsaturates. For higher pressures Kellogg has made available fugacity charts that go from 1000 to 3600 lb./sq.in.abs.

Instructions for use and sample calculations for bubble points, dew points and equilibrium flash points are included. The two volumes covering pressures from 14.7 to 1000 lb./sq.in.abs. are available as a package for $20. An additional $10 will be charged for the volume of fugacity charts. For copies, write the Chemical Engineering Division, The M. W. Kellogg Co., 225 Broadway, New York 7, N. Y.

DEPT. CHEM. ENG. AT NEW HAMPSHIRE UNIV.

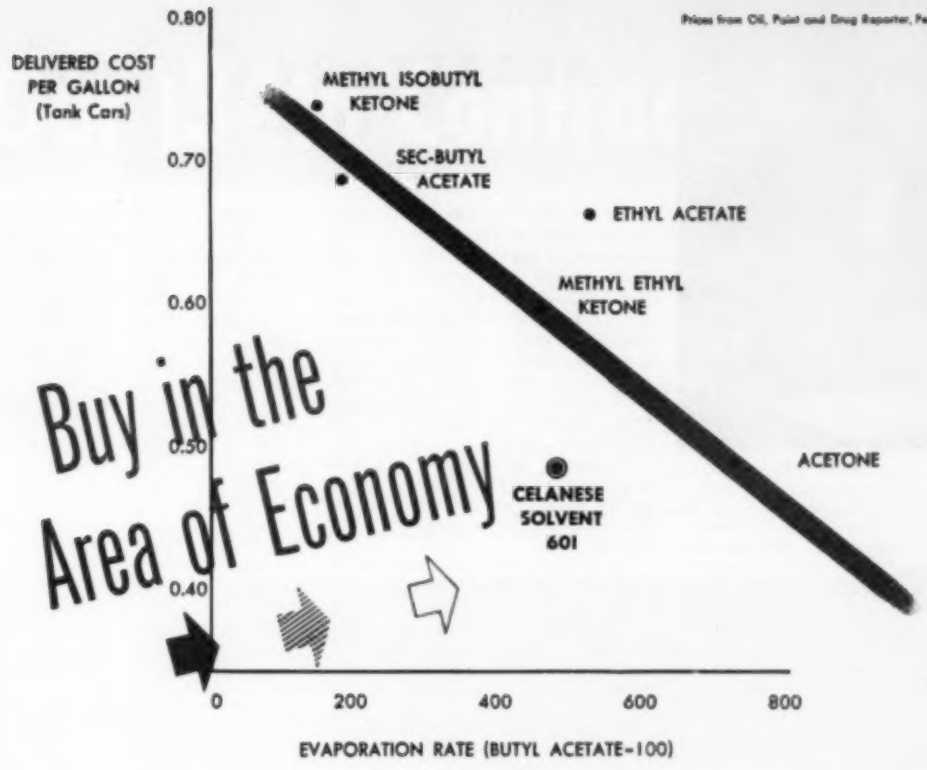
Creation of a department of chemical engineering, described as a significant step in aiding New Hampshire industry, was announced recently by the University of New Hampshire, Durham, N. H. Dean Lauren E. Seeley of the College of Technology said the new department is a response to the needs of New Hampshire where a recent survey showed the importance of chemical engineering in industry's development. The new department will be headed by Dr. Oswald T. Zimmerman, professor of chemical engineering, who has been teaching the subject in the department of chemistry. (*See* p. 46.) An authority on synthetic resins and hydraulic cements, Dr. Zimmerman has been at the University since 1938.

Effective next fall, the new department will have its laboratories in the $1,000,000 engineering building which is nearing completion. Although chemical engineering has been taught for a number of years, laboratory equipment has been limited because of a lack of space in the main chemistry building, James Hall. About one-half of the 150 students currently majoring in the field of chemistry are enrolled in chemical engineering.

RESEARCH CORP. GIVES GRANT TO UNIV. DENVER

A grant of $3,420 has just been received by the University of Denver from the Research Corporation, New York, N. Y., for support over a one-year period of research on oil shale. The sum has been awarded to Dr. Charles H. Prien, associate professor of chemical engineering, and a member of A.I.Ch.E., for a study of the "Effect of Solvent Configuration on the Depolymerization of Oil-Shale Kerogen." Kerogen is the oil-producing constituent of shale.

These funds are contributed gratis from Research Corporation's net earnings, as a "Frederick Gardner Cottrell Grant," named in honor of the corporation's founder.



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SECRETARY'S PAGE

S. L. TYLER

THE Executive Committee of the Institute met in the office of the Executive Secretary Feb. 10 and after approval of Minutes of the Executive Committee meeting of Jan. 6 reviewed the Treasurer's report and voted its approval. Payable bills were approved.

On behalf of Council the Committee approved for election, upon recommendation of the Committee on Admissions, all those whose names are listed below. It completed appointments to the various committees upon recomendation of the chairmen.

F. J. Van Antwerpen was appointed as alternate to J. R. Huffman on the National Research Council's Committee on Glossary of Terms in Nuclear Science and Technology.

James G. Vail was appointed Institute representative at the meeting of the American Academy of Political and Social Science to be held in Philadelphia, April 14 and 15.

C. G. Kirkbride was appointed Institute representative to work with the U.S.A. National Committee, to review papers from our members for possible presentation at the Third World Petroleum Congress, May 28-June 6, 1951, at The Hague, Holland.

Discussion was held on such matters as preparation of a new set of By-Laws for the Institute and several other matters regarding office procedures and records.

The new practice was initiated of the Executive Committee's reviewing the entire agenda for the Council meeting in order that Council meetings might be expedited and thus make available more time for the discussion of broad policy matters.

The Council of the Institute met on the afternoon of Feb. 10 at The Chemists' Club and among the items of business were the approval of Minutes of the Council meeting on Jan. 6 and the Executive Committee Meeting of the same date; also the appointment of Tellers to count the ballots on the amendments to the Constitution.

In accordance with the practice established last year one member of Council acts as liaison member for each of the standing committees of the Institute. These appointments were made.

Council approved the appropriation of $234.90 as our proportionate share of the budgeted expenses of Engineers Joint Council.

E. B. Christiansen of the University of Utah was appointed Institute representative at the celebration of the 100th Anniversary of the Founding of the University of Utah, Feb. 27 and 28.

Secretary reported that the Institute had been accepted as a member body of the American Standards Association. Our representative on the Standards Council of the A.S.A. will be T. H. Chilton, and E. H. Amick, alternate.

The Council appointed M. B. Conviser as an alternate of the Institute on the American Standards Association's new committee, the Chemical Industry Correlating Committee; our representative on this Committee is J. G. Lawrence and the other alternate is W. G. Fogg.

Several matters dealing with policy and the future of the Institute were discussed at considerable length but no decisions were reached so report on them will be postponed until final action is taken.

NEW A.I.Ch.E. MEMBERS ELECTED FEBRUARY 8, 1950

ACTIVE MEMBERS

Arnold M. Ames
William P. Bebbington
F. H. Belden
Norman Bell
Harold J. Born
William A. Casey
Leonard Hart Cirker
A. M. Cooley
William H. Corcoran
Malcolm M. Coston
A. Richard Downing
George James Dustin
Fred Eastman
J. W. Elston, Jr.
Charles F. Hauck
R. T. Henson
Donald C. Holmes
Emery Ikan
Walfred Jukkola
George Karnofsky
C. H. Kollenberg
Blaine B. Kuist
Willard E. Ledding
W. A. Lindenmaier
Louis F. Loutrel, Jr.
F. J. Maslyk
Lloyd R. Michels
John E. Morrow, Jr.
DeWitt O. Myatt
Charles L. Nickolls
Alfred H. Riley, Jr.
Kenneth T. Sloan
R. P. Stevens
Robert W. Timmerman
Edwin G. Willing
R. M. Willis
James H. Worth

ASSOCIATE MEMBERS

Lloyd E. Dean
H. A. LeBlanc, Jr.
Robert M. Neel
Rollin G. Taecker

JUNIOR MEMBERS

Jose Manuel Abreu
L. A. Adams
John George Athens
Frank Augustine
John D. Austin
Donald F. Barrett
George W. Bauserman
Robert B. Blomeyer
Robert A. Bogan, Jr.
Chas. D. Boyer, Jr.
Llewellyn Francis Brennecke
Robert A. Buckley
Key R. Caldwell
Kenneth S. Canfield
Paul Emerson Cherry
James F. Culverwell
William L. Engan
James B. Fleming
Irwin R. Friedman
Arthur E. Geers
J. Guilford Gerlach
Robert J. Getty
Shelby R. Gibbs
Wayne Glover
Bruce D. Hainsworth
R. Cameron Hammersley
Robert S. Herrod
Edward W. Holzknecht
Hugh J. Horne, Jr.
R. Jayaraman
Peter A. Kahn
Sam T. Kiguchi
Ellis M. Landsbaum
Robert M. Langer
Martin S. Maltenfort
Wayne E. McCoy
Richard E. Milana
Morton P. Moyle
Steven Muzik
David A. Nelson
Thorwell H. Paulsen
Peter A. Puleo
H. Maynard Rees, Jr.
William C. Richards
Lester E. Robb
Robert L. Robertson
Giuliano Romano
Paul R. Schweppe
Robert E. Siegfried
John E. Sigler
Olin K. Smith, Jr.
Charles W. Stager
Arnold H. Stern
David F. Stewart
Richard Platt Troeger
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LOCAL SECTION NEWS

SOUTHERN CALIFORNIA

The January meeting was held in the Wilmington refinery cafeteria of the Union Oil Company of California with 95 members and guests in attendance.

Jerome Kohl, head of industrial applications, Western division, Tracerlab, Inc., Berkeley, Calif., presented a highly informative and extensive talk entitled, "Radioisotopes—Their Properties and Engineering Applications."

It was amply demonstrated that the Atomic Energy Program has provided science with a valuable tool for research and production control by distributing radioisotopes. The current limitation to the uses of this new technique is now not radioisotopes but rather trained manpower. As more engineers and chemists become familiar with the inherent possibilities of this field, industry can expand its use of radioisotopes. Further progress in applications of radiochemistry is thus inevitable.

Officers for 1950 are:

Chairman—Ben M. Holt, The Ralph M. Parsons Co.
Vice-Chairman—Ira C. Bechtold, Fluor Corp.
Secretary-Treasurer—George R. Lake, Union Oil Company of California
Executive Committee—(Senior Member) Dr. F. J. Lockhart, University of Southern California
(Junior Member) William C. Gardner, C. F. Braun Corp.

Reported by G. R. Lake and G. Rosenblatt, Jr.

ROCHESTER

Officers of this section for 1950 are:

Chairman—Orrington E. Dwyer, Univ. of Rochester
Vice-Chairman—E. E. Mohr, Bldg. 23, Kodak Park, Rochester
Secretary—Earl W. Costich, Mixing Equipment Co., Rochester
Treasurer—H. G. Cooke, Bldg. 23, Kodak Park, Rochester

At the Feb. 15 meeting 21 members and guests attended the dinner at Lorenzo's and 32 the meeting held at the Rundel Memorial Library.

The speaker of the evening Paul S. Greer discussed "Cold Rubber." With the aid of photographic slides Mr. Greer gave considerable information on the production details for this material. He covered the properties of cold rubber and governmental control over its production. The program was concluded with the showing of a sound movie, "An American Story," by the Goodyear Tire & Rubber Co., dealing with the development of synthetic rubber.

Reported by Earl W. Costich

WASHINGTON-OREGON

Officers of this section for 1950 are as follows:

Chairman—F. R. Armbruster, 1702 Textile Tower, Seattle 1, Wash.
Vice-Chairman—F. B. West, Univ. of Washington, Seattle 5.
Secretary-Treas.—W. S. Munro, Monsanto Chem. Co., 911 Western Ave., Seattle 4.

Reported by W. S. Munro

ROCKY MOUNTAIN

This section wound up the year 1949 with a dinner meeting at Cunningham's Restaurant, Denver, Colo. Col. V. C. Huffsmith, Army Air Forces, gave a talk on "Patterns for War." Colonel Huffsmith is a graduate of West Point and since September, 1948, has been military consultant for Army Ordnance research at the Industrial Research Institute, University of Denver.

Reported by C. H. Prien

TULSA

Robert E. Fearon, nuclear physicist and director of research in the nuclear laboratories of Well Surveys, Inc., spoke Feb. 14 before a meeting of A.I.Ch.E. in Tulsa. He described the destruction which might be dealt to any populated port area exposed to a hydrogen bomb explosion. Such an explosion could be brought about by materials transported by unfriendly craft into the vicinity of any U. S. harbor.

Physical methods of policing against the delivery of such a blow are practically impossible to attain with information now generally available.

The general use of hydrogen bombs in a future war would hold a probability of complete destruction and disorganization of all civilized society, in Fearon's opinion. He urged that the U. S. build the hydrogen bomb immediately but also, because of lack of effective technological defenses against such bombs, the U. S. should spend an equal amount of money on efforts to bring about international accord on atomic weapons.

Reported by T. Q. Eliot

BATON ROUGE

Officers for 1950 are the following:

Chairman.....A. G. Keller
Vice-Chairman.....T. M. Smylie
Secretary.....J. C. Fedoruk
Treasurer.....R. H. Bretz
Executive Committee—
B. S. Pressburg
R. W. Richardson
H. M. Rodekohr
G. T. Piercy

The above-named officers were elected at the annual meeting held at the Heidelberg Hotel with 38 members in attendance on Dec. 15, 1949. Changes in the by-laws which changed the fiscal year to the calendar year to conform to the officers' tenure and a division of officers to provide for a secretary and a treasurer were approved.

Dr. Jesse Coates, a member of the section, presented a technical discussion on "Simplified Distillation Calculations." Principally, the subject involved the theatrical basis and practical application of obtaining minimum reflux ratio, the number of theoretical plates, and of estimating the distribution of components in the feed between the overhead and bottom products.

Reported by J. B. Killgore

TENNESSEE VALLEY

Names and addresses of the newly elected officers for 1950 are as follows:

Chairman—Cecil Rose, 1606 30th Ave., Sheffield, Ala.
Vice-Chairman—D. O. Walstad, House 95, Village 2, Sheffield, Ala.
Secretary—G. E. Stoltz, 76 Village 2, Sheffield, Ala.
Treasurer—G. C. Hicks, Highland Park, Sheffield, Ala.
Executive Committee Members—T. P. Hignett, 48 Village 1, Sheffield, Ala.; W. C. Saeman, 1907 Cloverdale Road, Florence, Ala.

Reported by D. O. Walstad

(*Continued on page 26*)

OFFICERS OF TWIN CITIES SECTION

Top: J. B. Calva, Ex. Comm.; W. M. Podas, Publicity Chm.; W. A. Carlson, Ex. Comm., and W. H. Goss, Ex. Comm. Bottom: R. J. Foster, Ex. Comm.; E. I. Piret, Chm.; R. H. Fredrickson, Sec.-Treas., and R. Stephenson, Vice Chm.

Could this mean a FORTUNE to you?

This cube melting in a man's hand is the metal—GALLIUM. Long recognized as an element, gallium is now commercially available. To what uses ingenious Americans will put it, is anyone's guess. Some already have started in a limited way.

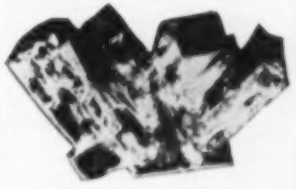
Every pound of bauxite, the ore from which aluminum is produced, contains a minute quantity of gallium. While no commercial method has been developed to extract all of this metal, Aluminum Company of America is now removing a small fraction of the gallium present in Alcoa bauxite, and is offering commercial quantities of it in high-purity metallic form.

Gallium presents properties that are indeed stimulating to scientists, researchers and development engineers—properties that open the door to possibilities in numerous fields.

Gallium has an unusually wide liquid range. Although it melts at body temperature, it will not boil until heated to about 3600° F. It "wets" the surface of many materials—can be painted on glass to make a brilliant mirror. And it expands when it solidifies.

We can't predict what the future holds for gallium, but we're betting there will be some amazing—and profitable—developments in the years to come. It may pay you to investigate this wonder metal. Gallium *could* mean a fortune to you!

Let us send you a free copy of our booklet *"Alcoa Gallium."* ALUMINUM COMPANY OF AMERICA, CHEMICALS DIVISION, 605C Gulf Bldg., Pittsburgh 19, Pennsylvania.



When allowed to solidify in ample space, gallium forms beautiful orthorhombic crystals.

Alcoa Chemicals

ALCOA

ALUMINAS and FLUORIDES

ACTIVATED ALUMINAS • CALCINED ALUMINAS • HYDRATED ALUMINAS • TABULAR ALUMINAS • LOW SODA ALUMINAS ALUMINUM FLUORIDE • SODIUM FLUORIDE • SODIUM ACID FLUORIDE • FLUOBORIC ACID • CRYOLITE • GALLIUM

FUTURE MEETINGS AND SYMPOSIA OF A.I.Ch.E.

Chairman of the A.I.Ch.E. Program Committee

George E. Holbrook

Room 7406 Nemours Bldg.,
E. I. du Pont de Nemours & Co.,
Wilmington, Del.

MEETINGS

Regional — Swampscott, Mass., New Ocean House, May 28-31, 1950.

Technical Program Chairman: R. L. Geddes, Stone & Webster Eng. Corp., Boston, Mass.

Co-Chairman: E. R. Gilliland, Massachusetts Institute of Technology, Cambridge, Mass.

Regional — Minneapolis, Minn., Sept. 10-13, 1950.

Technical Program Chairman: E. L. Piret, Minnesota Mining & Mfg. Co., Minneapolis, Minn.

Annual—Columbus, Ohio, Dec. 3-6, 1950.

Technical Program Chairman: John Clegg, Battelle Memorial Institute, Columbus, Ohio

Regional—Kansas City, Mo., May 15-16, 1951.

Technical Program Chairman: Walter W. Deschner, J. F. Pritchard Co., Kansas City, Mo.

Annual — Atlantic City, N. J., Chalfonte-Haddon Hall Hotel, Dec. 2-5, 1951.

SYMPOSIA

Indoor vs. Outdoor Plant Construction

Chairman: J. R. Minevitch, E. B. Badger & Sons Co., 75 Pitts St., Boston, Mass.

Meeting—Not scheduled.

Chemical Engineering Fundamentals

Chairman: Mott Souders, Shell Development Co., San Francisco.

Meeting—Minneapolis, Minn.

Chemical Engineering Kinetics

Chairman: R. H. Wilhelm, Princeton (N.J.) University

Meeting—Minneapolis, Minn.

Chemical Engineering in Food Industries

Chairman: W. L. Faith, Corn Products Refining Co., Argo, Ill.

Meeting—Minneapolis, Minn.

Phase Equilibria

Chairman: W. C. Edmister, Carnegie Inst. of Tech., Pittsburgh, Pa.

Meeting—Minneapolis, Minn.

Fluidized Systems in Chemical Syntheses

Chairman: E. R. Gilliland, Massachusetts Institute of Technology, Cambridge, Mass.

Meeting—Swampscott, Mass.

Ultrasonics

Chairman: Dudley Thompson, Virginia Polytech. Inst., Blacksburg, Va.

Meeting—Swampscott, Mass.

Applied Thermodynamics

Chairman: James Coull, University of Pittsburgh, Pittsburgh, Pa.

Meeting—Not scheduled.

Chemical Engineering in Glass Industry

Chairman: F. C. Flint, Hazel-Atlas Glass Co., Washington, Pa.

Meeting—Not scheduled.

Processing of Viscous Materials

Chairman: W. W. Kraft, The Lummus Co., New York, N. Y.

Meeting—Not scheduled.

Air and Water Pollution Control

Chairman: Richard D. Hoak, Mellon Institute of Industrial Research, University of Pittsburgh, Pittsburgh, Pa.

Meeting—Columbus, Ohio

Authors wishing to present papers at a scheduled meeting of the A.I.Ch.E. should first query the Chairman of the A.I.Ch.E. Program Committee, George E. Holbrook, with a carbon copy of the letter to the Technical Program Chairman of the meeting at which the author wishes to present the paper. Another carbon should go to the Editor, F. J. Van Antwerpen, 120 East 41st Street, New York 17, N. Y. If the paper is suitable for a symposium, a carbon of the letter should go to the Chairman of the Symposia, instead of the Chairman of the Technical Program, since symposia are not scheduled for any meeting until they are complete and approved by the national Program Committee. Before authors begin their manuscripts they should obtain from the meeting Chairman a copy of the Guide to Authors, and a copy of the Guide to Speakers. The first book covers the preparation of manuscripts, and the second covers the proper presentation of papers at A.I.Ch.E. meetings. Presentations of papers are judged at every meeting and an award is made to the speaker who delivers his paper in the best manner. Winners are announced in *Chemical Engineering Progress*, and a scroll is presented to the winning author at a meeting of his local section. Since five copies of the manuscript must be prepared, one should be sent to the Chairman of the symposium and one to the Technical Program Chairman of the meeting, or two to the Technical Program Chairman if no symposium is involved and the other three copies should be sent to the Editors' office. Manuscripts not received 70 days before a meeting cannot be considered.

LOCAL SECTION NEWS

(Continued from page 24)

KNOXVILLE-OAK RIDGE

This section held its annual meeting Jan. 12 at Brown's Restaurant, Knoxville. Officers elected were:

Chairman.....W. J. Hallett
Chairman-elect.....A. C. Jealous
Secretary.....W. B. Allred
Asst. Secretary.....F. S. Chance
Treasurer.....W. B. Harrison
Director.....J. O. Davis
Director.....R. N. Lyon
Director.....C. E. Winters

After the installation of the new officers, W. S. Farmer, graduate student in chemical engineering at the University of Tennessee, spoke on "Liquid-to-Liquid Extraction from Single Drops." Data for this paper were obtained in an investigation at Oak Ridge National Laboratory.

Rate equations, determined experimentally, were presented. Correlations relating the rate of solute transfer in a falling drop column to the properties of the system were discussed.

Reported by W. B. Allred and Robert M. Dowd

OKLAHOMA

This section held a meeting Jan. 20, 1950, in the Legion Rooms of the Civic Center in Bartlesville. The attendance was 28 members and guests.

Fred Prange of Phillips Petroleum Co. spoke on "Stress Sensitive Corrosion in the Oil Industry." His talk was illustrated with slides and samples of stress-corroded metals.

Officers of this section for 1950 are as follows:

Chairman.....John W. Palm
Vice-Chairman.....Harrison L. Hays
Sec'y-Treas......George E. Hays
Executive Committee Members—
Virgil Scarth
R. D. Snow
C. R. Ringham

AKRON

The February meeting was held at the Akron Art Institute and was attended by approximately 125 members and guests.

Mrs. Luke Lietzke, curator of industrial design, Akron Art Institute, spoke to the group on home design and furnishings. Following the lecture art exhibits were viewed and of particular interest were the displays of modern art in use.

Reported by J. W. Kosko

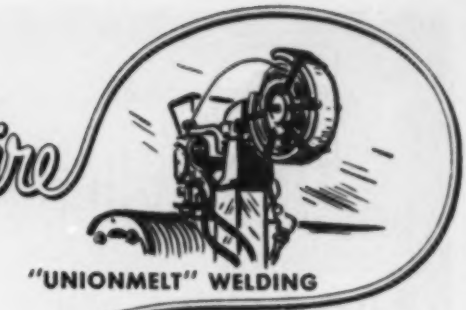
NEW JERSEY

A meeting of this section will be held in the auditorium of the Standard Oil Development Co., in its new research building in Linden, N. J., April 11.

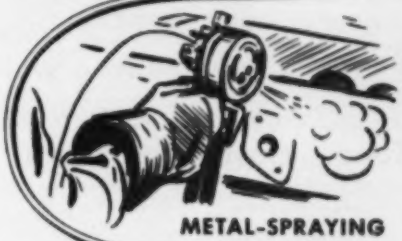
(Continued on page 28)

HASTELLOY TRADE-MARK *Alloy Wire*

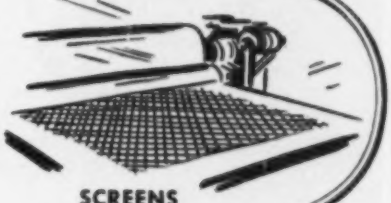
FOR METAL-SPRAYING, WELDING, and FABRICATED WIRE PRODUCTS



"UNIONMELT" WELDING



METAL-SPRAYING



SCREENS

HEAT-TREATING BASKETS

HASTELLOY nickel-base alloys, in the form of drawn wire, are available for the fabrication of corrosion-resistant screen, cloth, and baskets. The wire is also excellent for metal-spraying and for many types of automatic welding and hard-facing.

HASTELLOY alloys have a tensile strength comparable to that of the high-strength alloy steels, and possess unusual strength even at elevated temperatures. These alloys are specially designed to withstand the most severe conditions of chemical corrosion. Nickel-molybdenum alloy B is particularly resistant to hydrochloric and sulphuric acids, many organic acids, and all alkalies. Alloy C, a nickel-molybdenum-chromium-tungsten-iron composition, has excellent resistance to strong oxidizing agents, such as ferric chloride and wet chlorine, and is outstanding in its resistance to brine and salt spray.

In addition to HASTELLOY alloy wire, you can also obtain wire made of MULTIMET alloy—a cobalt-chromium-nickel composition developed for service at elevated temperatures.

Cut and straightened lengths or coils, in diameters down to 0.060 in., can be obtained directly from Haynes Stellite Company, Kokomo, Indiana. Wire in diameters less than 0.060 in. down to 0.002 in. is available from an associate company, Kemet Laboratories Company, Inc., Madison Avenue and West 117th Street, Cleveland 1, Ohio. For more complete information, write for a copy of the booklet, "HASTELLOY High-Strength, Nickel-Base, Corrosion-Resistant Alloys."

HAYNES TRADE-MARK *Alloys*

The terms "Haynes," "Hastelloy," "Multimet," and "Unionmelt" are trade-marks of Union Carbide and Carbon Corporation or its Units.

Haynes Stellite Division
Union Carbide and Carbon Corporation
UCC
General Offices and Works, Kokomo, Indiana
Sales Offices
Chicago — Cleveland — Detroit — Houston
Los Angeles — New York — San Francisco — Tulsa

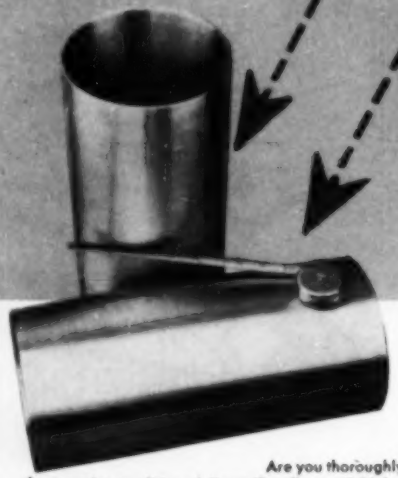
DURASPUN

18-8 Cylinder Liners

• True diameters

• True wall thicknesses

• Tough, close-grain metal



Are you thoroughly familiar with the superior qualities of "centrifugally cast" high alloys . . . such as these cylinder liners, for example?

Centrifugally cast metal is exceptionally uniform, close-grained and strong. It is free of pits and pockets. It is capable of passing very rigid tests. And the practical advantage is that as long as there is a central circular hole, almost any outside shape can be cast. Some of our customers want their castings centrifugal even though considerable boring and other machining is necessary to finish the piece.

We recommend our centrifugal casting service if your requirements call for the characteristics outlined above. Our high alloy foundry is modern in every respect and staffed by metallurgists and foundrymen of many years' experience with both centrifugal and static castings.

THE DURALOY COMPANY

LOCAL SECTION NEWS

(Continued from page 26)

DETROIT JUNIOR GROUP

This group heard Stephen V. Hart, chief engineer, Industrial Electronics, Inc., speak on "Industrial Electronics" on Feb. 7. Mr. Hart described the use of electronic instruments to measure the various physical and chemical changes occurring in chemical processes. He stated that the electronic system itself has been known for some time and is basically simple, but that the pickup system used to convey the change varies considerably, and the type used depends upon the property being measured or controlled. The chemical engineer, with his broader vision of instrumental problems occurring, could assist the electronics engineer immeasurably in the design of the pickup system to be used in a particular case. With some knowledge of the capabilities of electronic systems, the chemical engineer is in a position to suggest to the electronics industry many new applications.

Reported by P. A. Lenton

EAST TENNESSEE

The 24th general meeting was held in the Study Hall at Dobyns-Bennett High School, Kingsport, Tenn. James Herbert, sales promotion manager, Blue Ridge Glass Corp., discussed the many uses of glass in industry and had a number of exhibits to demonstrate the uses.

Officers elected for the year 1950 are as follows:

Chairman.....W. L. Campbell
Vice-Chairman.....W. G. Grubb
Sec'y-Treas.....R. H. Morrison, Jr.
Director.....R. E. Bevington

Reported by P. H. Schneider

ST. LOUIS

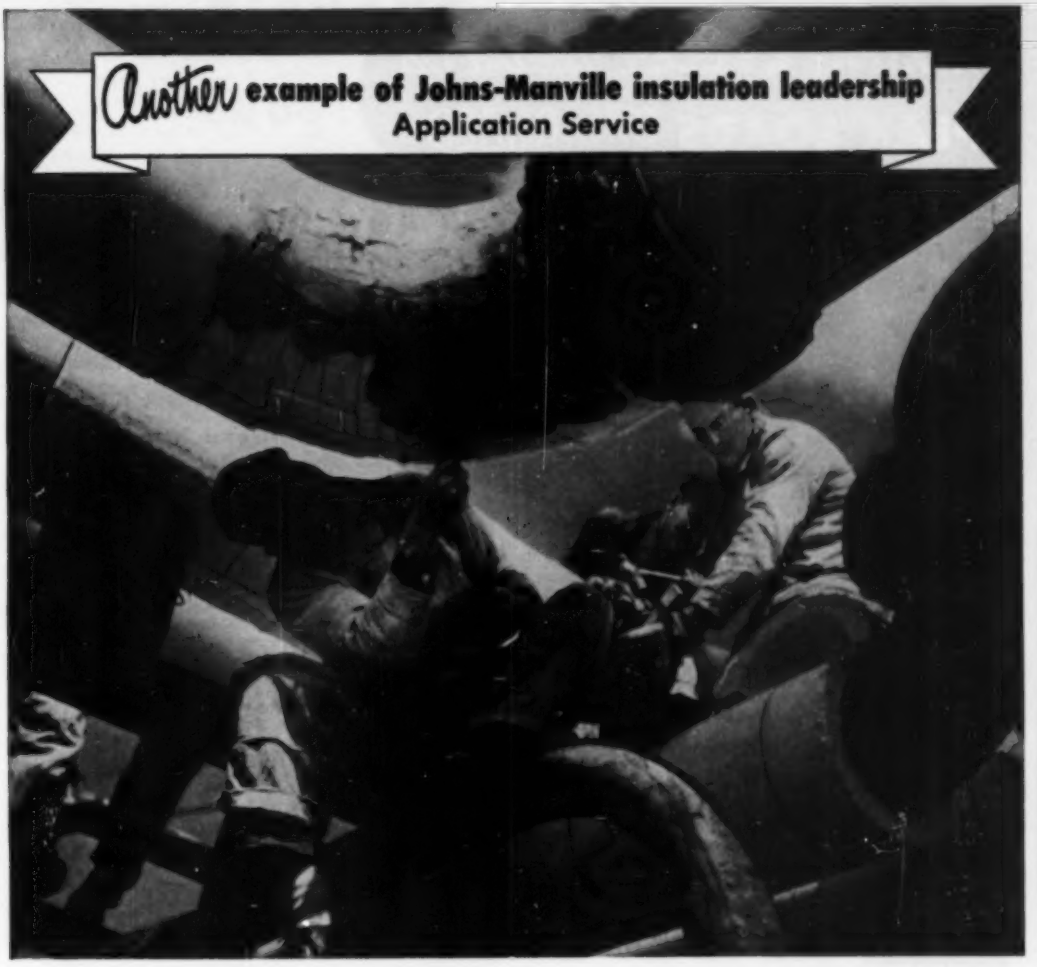
The January meeting was held in the York Hotel with 100 members and guests in attendance. The business meeting included a discussion of the A.I.Ch.E. National meeting for the year 1952.

At the conclusion of the business meeting Dr. Rodewald, Washington University, spoke on "Quantum Concepts in Chemical Engineering." He developed the history of the quantum theory and showed how the periodic table can be constructed on the basis of this theory. By its use certain peculiarities in the periodic table can be explained. It also explains certain crystalline structure formations and the binding of atoms together in a metallic state. All concepts of physics and chemistry can be explained by the use of quantum concepts.

Reported by R. S. Yates

(Continued on page 30)

Another example of Johns-Manville insulation leadership
Application Service



Bright future... for this insulation investment

Each day many men in industry ask themselves this question—*Just how should I go about getting the most out of each insulation dollar?* The answer, as with any investment, depends on several factors.

First, there's the reputation of the insulation manufacturer; the type of materials he has to offer; the efficiency of those materials in saving fuel. Next, there is the kind of service the manufacturer offers for engineering and applying his insulations.

This last consideration is a mighty important one. For, assuming all other things to be equal, it is the selection of the right insulation and the correct application of it that pays off in the long run on your insulation investment.

...And that's where Johns-Manville leadership in application service can be of utmost help to you. Your Johns-Manville Insulation Applicator selects the right materials for your specific job from the wide variety of J-M insulations that are available (for temperatures from minus 400F to 3000F above zero).

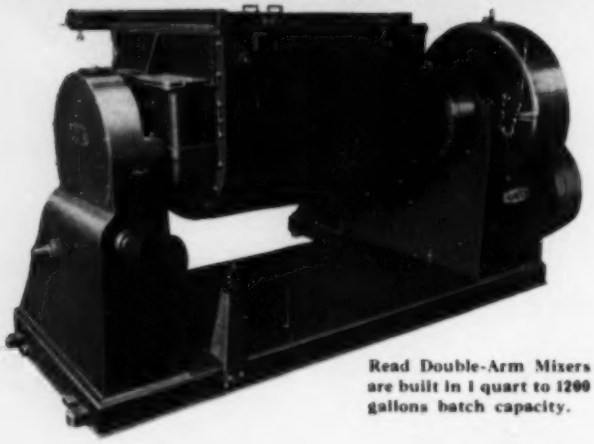
You will benefit by the long experience of your J-M Insulation Contract firm in all phases of insulation application . . . from engineering the job to the skill of his mechanics in applying the insulations.

If you have an insulation problem, write to the blue chip name for insulation investments—Johns-Manville, Box 290, New York 16, New York.

JM

Johns-Manville *first in* **INSULATIONS**

MIXING CYCLE *Speeded Up*
PEAK LOADS MINIMIZED



Read Double-Arm Mixers are built in 1 quart to 1200 gallons batch capacity.

OVERLAPPING SIGMA BLADE ACTION in READ Double-Arm Mixers gives you a *shorter mixing cycle* with *lower peak loads*

READCO CHEMICAL EQUIPMENT

Speeding up the mixing cycle and minimizing peak loads are definite advantages in batch mixers. Overlapping sigma blade action in *Read* Double-Arm Mixers does both. Formation of cylinders of material about the arms is avoided. They handle even the heaviest viscous materials with ease, smoothness, and production economy.

Some advantages: One-piece base to insure permanent alignment and rigidity—Mixing chamber accurately machined on double-arc bottom to insure close clearance with machined arms—Vacuum mixer has single packing gland construction to eliminate contamination or oxidation—Baffled jackets for even, efficient temperature control—Heavy-duty construction throughout—Available with or without jackets, of vacuum or non-vacuum design—Single, multi-speed, or variable speed motors for plastic processes.

Write Read for literature on Double Arm Mixers. If you have a mixing problem, let us offer you our advice.

READ

READ MACHINERY DIVISION
of The Standard Stoker Company, Inc.
YORK 5, PENNSYLVANIA

LOCAL SECTION NEWS

(Continued from page 28)

CLEVELAND

A meeting was held at Fenn College, Jan. 24, 1950. At the dinner the speaker was R. J. Wolf, B. F. Goodrich Chemical Co., who gave a brief history of the B. F. Goodrich Co. He traced its development from 1906, when it was established for the manufacture of analine as a rubber additive, through a series of later discoveries and applications which were responsible for the growth of the vinyl plastics industry. Another speaker was Hans J. Lang of Day and Zimmermann. Mr. Lang spoke on "Investment Cost Estimating."

Reported by E. N. Marsh

NEW ORLEANS

The executive committee adopted a standard schedule for meetings based on an analysis of previous meetings. This schedule includes six basic meetings a year as follows:

February (first Thursday, 8 P.M.) preferred or January (2nd or 3rd Thursday afternoon) if scheduled within Louisiana Engineering Society Annual Meeting
March (3rd Thursday, 8 P.M.). Joint meeting with Tulane Student Chapter
May (3rd Thursday, 8 P.M.).
September (1st Thursday after Labor Day, 8 P.M.).
October (2nd Monday, 8 P.M.) when meeting jointly with L.E.S. or
October (3rd Thursday, 8 P.M.).
December (1st Thursday, 8 P.M.). Annual Meeting, Election of Officers.

The interest of the ladies in forming a Ladies' Auxiliary to the section was discussed at a meeting of the executive committee Jan. 26.

Reported by R. M. Persell

EL DORADO CHEMICAL ENGINEERS' CLUB

An organization meeting was held in El Dorado, Ark., Nov. 8, 1949, to establish a chemical engineers' club to serve this general area. An executive committee was elected as follows:

Chairman—C. H. Davenport, Lion Oil Co.
Vice-Chairman—J. W. Bertetti, Pan-Am. Southern Corp.
Sec'y-Treas.—R. R. Gumaer, Pan-Am Southern Corp.

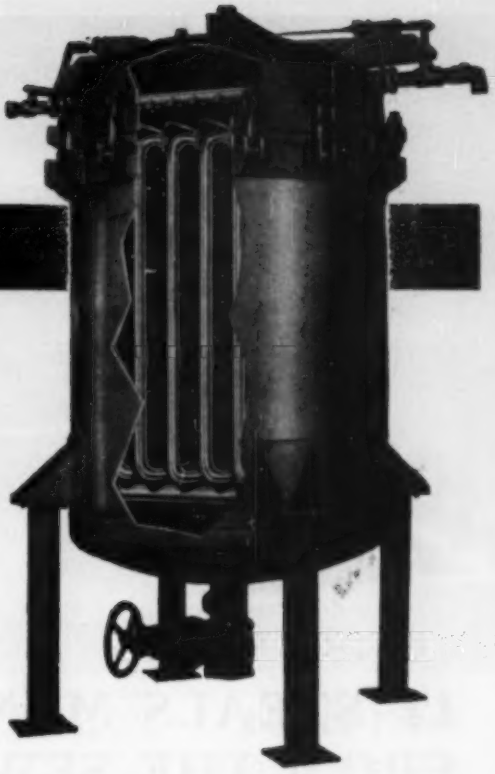
The first dinner-speaker meeting of the new club was held in El Dorado, Jan. 26, with an attendance of 55. After a short business session in which the aims of the club, membership details were outlined, O. C. Bailey of El Dorado, chairman, Arkansas Oil and Gas Commission, gave an address entitled, "A Decade of Petroleum Conservation in Arkansas."

Reported by C. H. Davenport

(Continued on page 33)

Now NIAGARA adds

SELF CLEANING



TO ITS LONG LIST OF FEATURES

"Auto-Sluice" **Removes 35 Cu. Ft. Filter Cake in 15 Minutes Automatically**

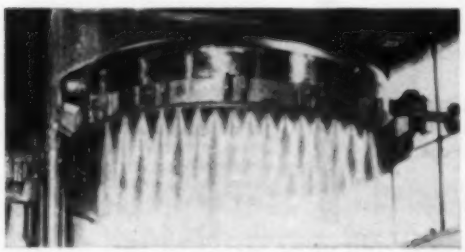
No more do you have to open the filter at the end of each cycle to sluice the cake from the leaves. Niagara now offers the "Auto-Sluice" filter which permits automatic cake removal and disposal. A special filter cover is fitted with a header and special spray nozzles so located and directed that sprays strike the cake of each leaf. This sluice header is actuated by air motors which impart both a rotary and reciprocating motion assuring thorough sluicing of all surfaces.

The new Niagara "Auto-Sluice" can remove filter cakes up to 35 cubic feet in as little as 15 minutes with only two or three cubic feet of water per cu. ft. of filter cake. Here are savings in time, labor and sluice water consumption you cannot afford to overlook. Send for literature on this new Niagara Filter which has already proved its ability to effect sizeable savings in sugar, food, and chemical plants.

Add these "Auto-Sluice" Features to Niagara's Stainless, Clothless Filters:

1. **Reduction of Labor Costs.** Eliminates opening and manual cleaning of filter after each cycle.
2. **Reduction of Unproductive Time.** Short sluicing time increases productive filtration time and capacity.
3. **One Man Battery Operation.** A battery of as many as six Niagara "Auto-Sluice" Filters can be handled by one operator.
4. **Automatic Filter Cake Handling.** Totally closed system for removing cake from leaves and discharging to sewer or for recovery.

* *Trade Mark Patent Applied For*



Testing "Auto-Sluice" sprays with cover open. These powerful sprays, in the course of each full rotary and reciprocating stroke, cover the entire filter leaf area.

Niagara Filter CORPORATION

3084 MAIN ST., BUFFALO 14, N. Y.

NIAGARA FILTER CORP.
3084 Main St., Buffalo, N. Y.

Please send me literature on the Niagara "Auto-Sluice" Filter

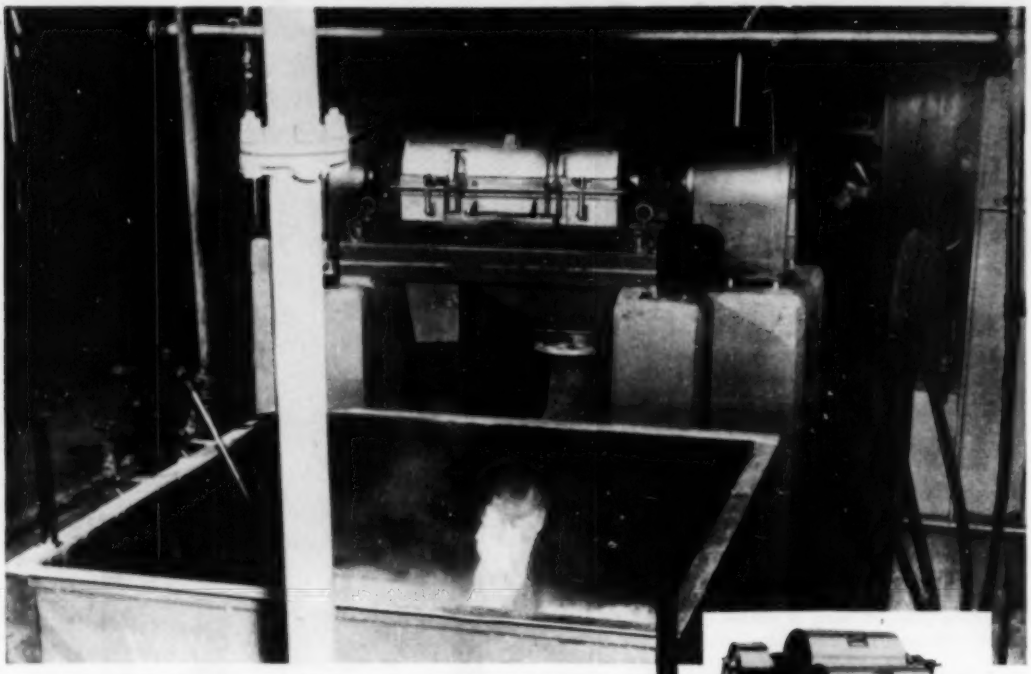
NAME _____

TITLE _____

COMPANY _____

ADDRESS _____

CITY _____ STATE _____



IT STEALS MONEY FROM THE SEWER

Many plants have needlessly accepted the loss of valuable solids in waste water and process liquors—believing them to be uneconomical to reclaim. The plant shown above formerly was one of them.

TODAY, continuous super filtration provided by the Sharples Super-D-Canter is not only removing solids economically, but it is doing so at a substantial profit.

In addition to removing solids, the Sharples Super-D-Canter is used for the clarification of liquids, or it is adjustable for use as a classifier: removing solids within a set size range.

The Super-D-Canter is continuous; both in the discharge of liquids and the discharge of solids. It can handle a wide range of slurries and do a better separating job because it develops the highest centrifugal force of any centrifuge of this type.

Complete information will gladly be sent to you.

TWO BASIC TYPES

The two types of Sharples Super-D-Canters provide for the successful handling of practically any slurry. Depending on individual characteristics, solids may range from 1% to above 50%.

The Sharples *Conical* Super-D-Canter is used for firm-bodied type solids; while the *Cylindrical* Super-D-Canter is especially designed for soft and amorphous, extrudable-type solids.

Since the Sharples Corporation manufactures *the complete line* of all centrifugals, you can always be assured that their recommendations are impartially based on the best fulfillment of your particular requirements.

THE SHARPLES *Sharples* **CORPORATION**

NEW YORK 17, N.Y. CHICAGO 4, ILL. BOSTON 10, MASS. SAN FRANCISCO 5, CALIF. CLEVELAND 15, OHIO

EXECUTIVE OFFICES AND FACTORY, 2300 WESTMORELAND STREET, PHILADELPHIA 40, PENNA.

Chemical Engineering Progress

DATA SERVICE

CHEMICALS

1 • *GLYCERINE FOR RESINS.* As part of a regular service on the use of glycerine in industrial products, the Glycerine Producers' Association now publishes a study of typical glycerine uses in alkyd resins and ester gums. This is fifth in a series and this book contains data along the similar lines of previous booklets. Contains references, physical properties, graphs and tables on glycerine properties.

2 • *ACID INHIBITOR.* A technical bulletin on Hibitite acid inhibitor manufactured by the Monsanto Chemical Co. Primarily designed for use in the steel industry for pickling, the material may be used also for cleaning drums, sand filters, etc. Available as a dry powder, or already mixed in sulfuric or muriatic acid.

3 • *MALEIC ANHYDRIDE.* From Carbide & Carbon Chemicals Division comes a booklet describing maleic anhydride in a new physical form. It is produced in small hollow cylinders. Bulletin which gives the physical properties, specifications, uses, reactions and bibliography of maleic anhydride.

4 • *SOLUBLE SILICATES.* A bulletin containing technical data on various types of Philadelphia Quartz Co. soluble silicates, gives technical data on the rate of solution of powdered silicates, plus approximate compositions.

5 • *FLAME-SPRAYING POLYETHYLENE.* A data sheet on the method of flame-spraying polyethylene with the Schori pistol tells how polyethylene coatings and films are applied to metal, concretes, ceramics, etc. Describes also the flame pistols and capacities.

6 • *TICK REPELLANT.* The Dow Chemical Co. announces that it has available semicommercial quantities of N-butylacetanilide, a chemical that shows good promise of being a good tick repellant.

7 • *ZIRCON FOUNDRY SAND.* A complete bulletin on the use of Zircon foundry sand has been issued by the Millmaster Chemical Corp. Gives prices, analysis, advantages, and formulations for mixing the Zircon foundry sand with other chemicals to make cores, etc.

8 • *SILVACON.* A 4-page bulletin from Weyerhauser Timber Co. explaining industrial uses. Silvacon is a natural plastic derived from Douglas fir bark. Physical and chemical properties are given.

9 • *CHLORINATED RUBBER PAINTS.* From Hercules Powder Co., manufacturer of chlorinated rubber, a discussion on the advantages of using maintenance paints having a chlorinated rubber base. The folder briefly discusses outstanding chemical resistance and suggests many applications for the chemical processing industries.

10 • *DIHYDRAZINE SULFATE.* Semicommercial quantities of dihydrazine sulfate are being produced by Mathieson Chemical Corp. Has 37½% available hydrazine for organic synthesis, insecticides, herbicides, polymerization of vinyl resins, reducing agents for metal finishing, etc. Technical data sheet giving physical properties, uses, reactions, etc.

11-12 • *AMINO ACIDS.* Two publications, the first in a series of publications on the essential amino acids, have been published by the Dow Chemical Co. Of importance to industry, the first (67) covers Tryptophan; the second (68) covers Methionine.

14 • *TITANIUM DIOXIDE.* American Cyanamid Co. announces several improved types of titanium dioxide. One is particularly suited for high temperature baking enamels, refrigerator finishes, lacquers, and phenolic resins. A second development is slated for use with enamel finishes and Maelic modified vehicles. This same product performs a special function for metal decorative roller coatings and alkyd baking enamels.

BULLETINS

15 • *CAUSTIC SAFETY CHART.* Solvay Sales has a new safety instruction chart for caustic soda users. This is the third in its series of wall charts instructing personnel in the handling of dangerous chemicals. Chart contains suggestions for protecting employees, unloading precautions, etc. It is printed on heavy stock for wall display.

16 • *ION EXCHANGE.* From the Permutit Co., a 12-page pamphlet on ion exchange giving history of

Mail card for more data ▶

Cards valid for only six months after date of issue

Chemical Engineering Progress Data Service

I would like to obtain more information on the items represented by the numbers I have circled.

1	2	3	4	5	6	7	8	9	10	11	12	14	15	16
17	18	19	20	21	22	23	24	25	26	27	28	29	30	32
33	34	35	40	41	42	43	44	45	46	47	48	49	50	

Name _____ Position _____

Company _____

Address _____

City _____ Zone _____ State _____

the company, selection of ion exchangers, types of ion exchangers available, flow diagrams of five basic types, cutaway view of some equipment, and brief mention of applications and installations.

17 • ***ALLOY REFERENCE CHART.*** A 6-page folder chart containing analysis, mechanical properties, applications, etc., of alloys, has been prepared by N. S. Mott of the Cooper Alloy Foundry Co. It contains alloy types as well as comparative designations of the Alloy Castings Institute, AISI, SAE, ASTM, etc. Gives mechanical properties such as tensile strength, yield point, elongation, Brinell; tells where they should be used and gives data on corrosion resistance.

18 • ***PFAUDLER LINE.*** A 4-page folder which briefly details the type of equipment and materials of construction offered by the Pfaudler Co. Briefs the heat treatment, pressures, temperature, metal thicknesses, finishes and shapes, etc., and illustrates some special process equipment made by this company. Designed to acquaint the industry with the types of services and materials of Pfaudler.

19 • ***AIR COOLERS.*** For the engineering task of cooling liquids or gases with air, the American Locomotive Co. gives a great amount of data concerning its Alco air coolers. For the plant that has a problem in obtaining sufficient water for cooling, forced draft heat-transfer equipment such as this becomes important. The pamphlet gives mechanical specifications, layouts, plans of such equipment, data on selecting the best air coolers from the heat load involved, etc., gives some information on field erection, costs, etc.

20 • ***GAS FOR INDUSTRIAL HEATING.*** Copies of a talk by F. O. Hess of the Selas Corp. on the use of gas as an industrial processing tool. In this article which was given before a conference on combustion at the University of Tennessee, use of gas in industrial processing is traced, beginning with magazine printing and drying of ink, use of radiant gas burners to flow tin on electrolytically deposited sheet, use in steel annealing, making of fluorescent lamps, and other processing information.

21 • *22* • ***INSULATED PIPING SYSTEMS.*** Two data books on the Ric-Wil insulated piping systems for distributing steam, hot water, oil, etc. Ric-Wil offers them in two types, prefabricated in self-contained units, and sectional, signifying that parts are furnished separately and assembled at the job. No. 21 describes the Ric-Wil pipe units, and gives general specifications for various systems (underground or overhead), how to support pipes, excavation, back-filling, hangers, and supports, etc. Many tables on properties of pipe, giving diameters, weights, capacities, expansion charts, heat losses, schematic diagrams showing arrangements, and much other information. No. 22 is a description of the pipe units themselves. Well illustrated with pictures, shows installations and capacities of the company fabricated units.

23 • ***PROTECTIVE COATINGS.*** Five types of protective coatings made by the Atlas Mineral Products Co. Under each of the five coatings there is a series of special and modified coatings. Under synthetic thermoplastic resins in selected solvents, the company makes protective coatings of polyvinyl, polyvinyl plus a non-volatile synthetic rubber plasticizer, and styrene copolymer. Application and use are described under basic types which are asphaltic and furane-base resins. Altogether 11 different protective coatings are described.

24 • ***HAMMER MILL.*** From Sprout-Waldron, a package which gives detail of a new hammer mill. Drawings give construction details, an instruction card shows how hammer mills are installed, how to inspect and care for the equipment, etc.

25 • ***STEELS FOR HIGH TEMPERATURE.*** A 90-page book from United States Steel on the correct choice of steel for elevated temperature service. Begins with a discussion of the general principles of elevated temperature behavior of steel, and a brief description of test methods and laboratory techniques used. Then a data section follows with tabular and graphical material on 21 different steels, which gives, in addition to physical properties over a range of temperatures, the applications of the particular alloy under consideration. Also discusses hot forming, welding, etc. Another section describes the research facilities and laboratories and special equipment used by the company in making tests, and the final few pages are given over to a bibliography of publications from the United States Steel Corp. on the use of steels at elevated temperatures.

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DATA SERVICE

26 • SPECTROGRAPHIC OUTFITS. A Jarrell-Ash Co. bulletin on spectrochemical analysis which features the Hilger prism. Pamphlet describes the prism spectrograph, gives specifications and describes supplemental equipment, construction details, advantages, uses, etc.

27 • MIXED-BED DEIONIZATION. A description of the Illinois Water Treatment Co.'s new mixed-bed deionization system. The new system makes use of a single column containing an intimate mixture of cation and anion exchange resins. According to the company, the correct design of the column will enable the mixed bed to be separated, regenerated, and remixed in a single exchange vessel. Bulletin available.

28 • PORTABLE DUST COLLECTOR. For removal of dust from factory atmospheres, the Kirk & Blum Manufacturing Co. has newly developed heavy-duty dust collectors available in capacities of 450, 900, and 1800 cu. ft./min. The dust collectors can be set up at any place in the processing unit eliminating the need for collection pipes. The dust passes through a centrifugal precleaner, and then a steel-wool filter. Discharge can be either to outside or inside of the building depending upon the season. After-cleaner is easily reached and dust bin allows for removal of dust separated by centrifugal cleaner.

29 • SAFETY EQUIPMENT. A catalog released by the General Scientific Equipment Co. covers respiratory devices, eye protection, hats, gloves, carboy pumps, drum pumps, etc. Its 46 pages are well illustrated. Prices are generally given for item described.

30 • PROTECTIVE COATING. A bulletin from the Maurice A. Knight Co. describes Pyroflex synthetic resin lacquer coatings for resistance to most acids, alkalis, salts, oils, etc. Tells of uses to which lacquer is put, gives instructions for applying, equipment to use (spray gun) and data on protection afforded with this lacquer against chemicals.

32 • 33 • FILTER MEDIA. T. Shriver & Co., Inc., have two new pamphlets on filtration. The first, No. 32, is on filter media and describes briefly the cotton, wool, synthetic resin, glass, metallic, and paper filter media that they manufacture. Gives briefly the materials which can be filtered with these media. No. 33 is a new periodical—Filter Facts, which not only gives information on filter presses and filtration, but also describes some new pumps such as diaphragm pumps, proportional pumps that Shriver makes. Also contains information on filtration techniques.

34 • INJECTION MOLDING PRIMER. Tennessee-Eastman has a book on "Tenite Injection Molding." Contains detailed data on the injection molding of cellulose acetate, and cellulose acetate butyrate thermoplastics. A complete primer of injection molding, contains detailed data on choice of materials, proper product design, machines, mold design and construction, etc.

35 • LEKTROMESH. A bulletin explaining the wire mesh product of the C. O. Jelliff Mfg. Corp. The screen is continuous, being made by electroforming. Extremely accurate tolerances. Range in mesh from 25 to 400. Produced in nickel and copper. For use as a screening medium in the chemical processing of food, oil, etc., industries.

EQUIPMENT

40 • GRAPHITE GLOBE VALVE. From the National Carbon division of the Union Carbide & Carbon Corp., comes the announcement of a new graphite globe valve available in 1-in. and 2-in. sizes. Designed especially for service with corrosive fluids, the new valve features all Karbate parts with the exception of the Teflon packing. Resistant to most corrosive chemicals; can be heated from the outside with a steam coil for handling highly viscous or saturated solutions. Bulletin available.

41 • EXPLOSION-PROOF FLOAT. An explosion-proof float-operated electric controller for liquid storage systems, has been developed by McDonnell & Miller. The equipment is designed for use under conditions where the conventional-type controller is not applicable. Two types available—one for atmospheres containing ethyl-ether vapors, ethylene, or cyclopropane; the other for atmospheres containing gasoline, petroleum, naphtha, benzine, etc. Will make or break electric circuits at high level. Descriptive circular available.

42 • TEMPERATURE CONTROL. For holding fluid temperatures within a range as narrow as ± ½° F., the

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DATA SERVICE

Pako Corp. has a new temperature-control device. The unit circulates a tempering liquid through a jacket or tempering panel surrounding the critical fluid. A heat-exchanger is incorporated which provides heat or refrigeration as required, to the tempering liquid which circulates through a closed circuit.

43 • VACUUM PAN DRIER. For the recovery of dry solids by evaporation of solutions or slurries, Industrial Process Engineers have a new stainless steel vacuum pan-drier. Working capacity up to 35 gal. and working pressures up to 50 lb./sq. in. The agitator has no internal bearing, and consists of an anchor with spring-loaded scrapers driven at 40 rev./min.

44 • TWIN-BLENDER. A unique mixing apparatus for blending dry materials, consisting of two cylindrical shells of equal diameter but joined together to form a V rather than a long tube, is a new product of the Patterson Kelly Co. The V-shaped unit rotates about a horizontal axis. Material is fed through either leg of the V and a discharge valve is located at the apex. Company claims superior mixing times and sizes of the new blender range from 1 to 250 cu. ft. Capacity and power requirements vary according to density of material. Company also has available small test blenders of transparent plastic for visual checking during test periods. Literature section available.

45 • ABSORPTION HEATING. For the drying of heat-sensitive materials even while frozen, Proctor & Schwartz, Inc., have a new unit based on the absorption of infrared radiation. The process was developed by the Dry-Freeze Corp. and P. & S. are manufacturers of the equipment. The unit uses certain effective wave lengths of infrared radiation in the fundamental vibration region where radiant energy is absorbed selectively by different materials depending upon their chemical composition. It is possible to select radiation in a region where the greatest percentage of the total energy will be absorbed by the water in the product to be dried. This makes it possible to dry materials which are damaged by temperatures of above 100° F.

46 • REVERSIBLE CONTROL VALVE. An air-operated control valve, which can be changed in a few minutes' time from an air-to-open to an air-to-close valve, is a new development of the Foxboro Co. The quick reversibility of the air control valve will be a feature of convenience in test work or pilot plant operation where equipment or flow changes become necessary. The valve makes use of a new reversible motor and the action of the valve motor is reversed merely by moving the housing assembly and rotating it a quarter-turn.

47 • PORTABLE CHEMICAL FEEDER. From the Gifford-Wood Co. an announcement of a new portable screw feeder for metering dry chemicals from original drum containers to mixing kettles. It consists of a 4-in. diameter screw conveyor driven by a ½ hp. variable speed motor reducer. It will operate at from 3 to 9 cu. ft./hr. Entire unit is mounted on swivel casters and has a moisture-proof housing.

48 • IMMERSION HEATER. A series of stainless electric immersion heaters for use with industrial chemicals, alkaline cleaners, oils, corrosive liquids, etc., is offered by the Edwin L. Weigand Co. Constructed of hair-pin-shaped heavy duty Chromalox elements, they are available from 1 kw. to 15 kw. Voltages of 230, 460, and 550. The company will make specific recomendations for corrosive application.

49 • SPRAY DRYER. A portable spray dryer for pilot plant use, selling for $3500, is a new feature of the Niro Corp. It is easily transported from one department to another and features a high-speed atomizing head rotating at 50,000 rev./min. which ejects the liquid product as a fine mist into the drying chamber. Literature is available from the company explaining principle. Unit is equipped with both electric and gas heating element and capacity is 2 to 15 lb. of water evaporated/hour.

50 • ROOM DEHUMIDIFIER. For control of humidity in rooms up to 8000 cu. ft. volume, Fisher Scientific Co. has introduced a new dehumidifier. It contains condensing and evaporating coils, motor-driven fan, and a receptacle for condensate. It is 14 in. in diameter, 34 in. tall, and is operable wherever dew point is above 50° F. or dry bulb reading of hydrometer is above 65° F.

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LOCAL SECTION NEWS

(*Continued from page 30*)

CHICAGO

The monthly dinner meeting was held at the Western Society of Engineers, Jan. 18 with approximately 125 in attendance. After dinner, J. B. McMahon addressed the group on "Process Factors which Affect Automatic Control." Mr. McMahon is vice-president of the Instrument Society of America and manager of sales promotion for the Republic Flow Meters Co. His talk concerned primarily the correct application of automatic controls to the industrial process and was interestingly explained by many personal experiences.

The local section is planning a special meeting in April to which all members of the student chapters of A.I.Ch.E. at Illinois Institute of Technology and Northwestern University will be special guests.

Reported by Donald A. Dahlstrom

LOUISVILLE

Howard E. Degler, technical director, Marley Co., Kansas City, spoke at the February meeting. Mr. Degler chose as his subject "Water Cooling Towers as Related to Water Conservation."

The growing importance of water conservation was stressed in terms of increased demands, inadequate distribution facilities, and pollution problems. Mr. Degler then discussed fundamental principles on which design of water-cooling towers is based. Curves relating costs to tower operating conditions and slides showing such units in operation presented the practical side of this topic.

Reported by W. B. Altsheler

CENTRAL OHIO

E. D. Turnbull, chemical engineer, The Euston Lead Co., Scranton, Pa., addressed this section on "A Chemical Engineer in Australia," Jan. 27, 1950.

In his address Mr. Turnbull gave an account of the experience of an American chemical engineer in starting a new white lead plant in Melbourne, Australia.

Mr. Turnbull's talk was followed by a business meeting at which the following officers were elected for the year 1950:

Chairman—Dr. Albert W. Davison, Owens Corning Fiberglas Co., Newark, Ohio

Vice-Chairman—Edward A. Beidler, Battelle Memorial Institute, Columbus, Ohio

Secretary—Dr. John W. Clegg, Battelle Memorial Institute, Columbus, Ohio

Executive Committee—Dr. Ralph Vogel, National Lime and Stone Co., Carey, Ohio; Dr. James O. Pence, Kanco Inc., Columbus, Ohio; Joseph H. Koffolt, Past Chairman, Ohio State University

Reported by J. H. Koffolt

(*Continued on page 34*)

SPROUT-WALDRON'S

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THE MODERN AIR CONVEYOR SYSTEM

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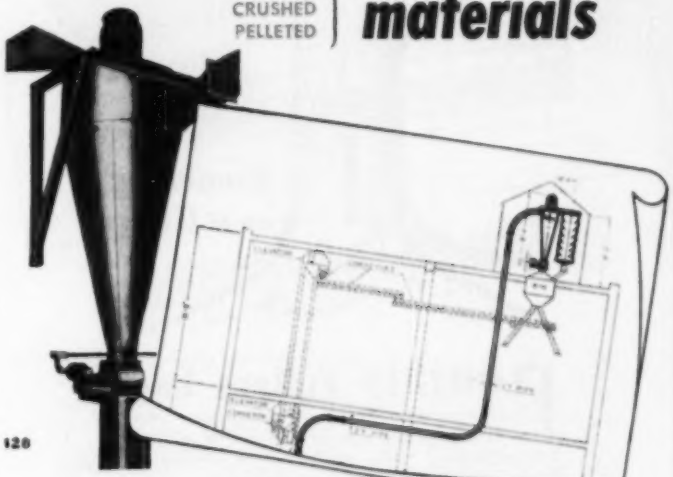

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LOCAL SECTION NEWS

(Continued from page 33)

SOUTH TEXAS

The January meeting of this section was held jointly with that of the ACS at Baytown, Tex., Jan. 26, 1950. No inspection trip was scheduled and the opening event of the meeting was a dinner at the Humble Dining Room. This being a joint meeting business was confined to announcements of common interest. The speaker for the evening was Dr. H. S. Taylor of Princeton University who spoke on "Factors Affecting the Rate of Chemical Reaction of Organic Molecules."

Officers for the calendar year 1950 were announced as follows:

Chairman—William A. Cunningham, University of Texas
Chairman-elect—W. E. Alexander, Monsanto Chemical Co.
Secretary—James A. Lee, McGraw-Hill Publishing Co.
Treasurer—R. N. Blaize, Eastern States Petroleum Co.
Executive Committeemen—L. B. Dampman, Carbide & Carbon Chemicals Corp.; H. K. Eckert, Monsanto Chemical Co.; G. T. McBride, The Rice Institute.

Reported by G. T. McBride

OHIO-PITTSBURGH

Symposium

A one-day symposium, "The Development and Marketing of New Chemical Products," sponsored by the Akron, Central Ohio, Cleveland, Detroit, Ohio Valley and Pittsburgh Sections of A.I.Ch.E. will take place April 14 at the Hotel Hollenden, Cleveland, Ohio. The program chairman is R. L. Savage, Case Institute of Technology.

The following list of papers is scheduled for presentation:

PROGRAM

Morning Program

Development of Markets for Isocyanates in the U. S.—*Paul Logue, Monsanto Chemical Co.*

The Disco Development—*F. O. Calhoon and W. D. McElroy, Pittsburgh Consolidated Coal Co.*

Commercial Market Development of Emery M-461-R Dimer Acid—*R. D. Aylesworth, Emery Industries, Inc.*

The Organization of a Technical Service Group for a Newly Organized Chemical Company—*Gilbert Thiessen, Koppers Company, Inc.*

LOCAL SECTION NEWS

Afternoon Program

Technical Development and Marketing of Glass Fibers—*E. H. Bolz, Glass Fibers, Inc.*

Residual Fuels; the Economic Effect of New Refining Techniques—*R. H. Collacott, Standard Oil Co. of Ohio.*

Furan Chemicals—*Harold J. Barrett, Electro Chemicals Dept., Du Pont Co.*

Economic Aspects of the Development of Fuel Gas from Coal—*John S. Foster and Richard J. Lund, Battelle Memorial Institute.*

Address inquiries to W. S. Shellentrager, c/o Standard Oil Co., 2735 Broadway Ave., Cleveland 13, Ohio.

Reported by D. L. Farrell

WESTERN NEW YORK

This section held a meeting Feb. 16 at the University Club, Delaware Ave., Buffalo. W. H. Doyle, chemical engineer, Factory Insurance Association, gave a talk entitled, "Wild Chemicals I Have Known." Mr. Doyle discussed some interesting fires and explosions that have occurred in chemical plants and gave a résumé of what insurance people are trying to do in cooperation with industry to keep such losses to a minimum.

Reported by Earl C. Mirus

BOSTON

Officers for the year 1950 are as follows:

Chairman—Neal A. Sargent, 38 Pierrepont Road, Winchester, Mass.

Vice-Chairman—Austin W. Fisher, Jr., 1303 Mass. Ave., Lexington, Mass.

Secretary—Henry Avery, c/o Godfrey L. Cabot, Inc., 77 Franklin Street, Boston

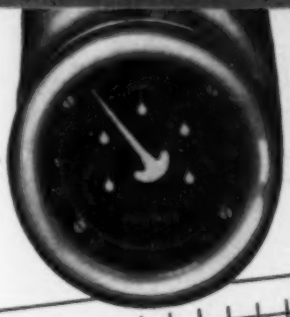
Treasurer—Peter M. Rinaldo, 382 Marrett Road, Lexington 73, Mass.

On Jan. 20 this section heard Stephen Tyler, the National Secretary, as its guest speaker, give a talk on Institute affairs and activities.

At this meeting John J. Healy, A.I.Ch.E. director and National chairman of the Local Sections Committee, presented the Program Committe's Award for quality of presentation of papers to Dean T. K. Sherwood, of Massachusetts Institute of Technology for his paper presentation at the Twelfth Regional Meeting held in Montreal, Sept. 6-9, 1949.

Reported by Henry Avery

ANOTHER IMPORTANT FEATURE OF SHUNTFLO STEAM METER



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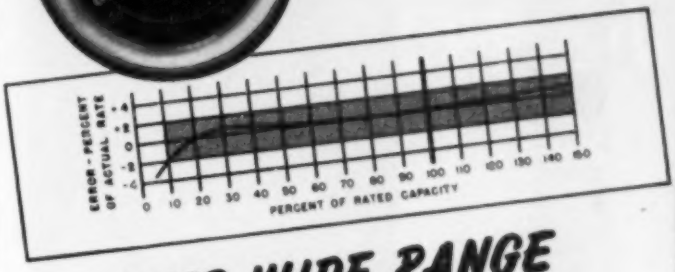

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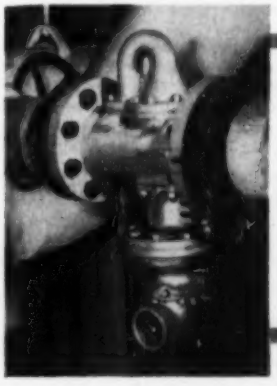

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Chlorinizers — Chlorine Gas Feeders.

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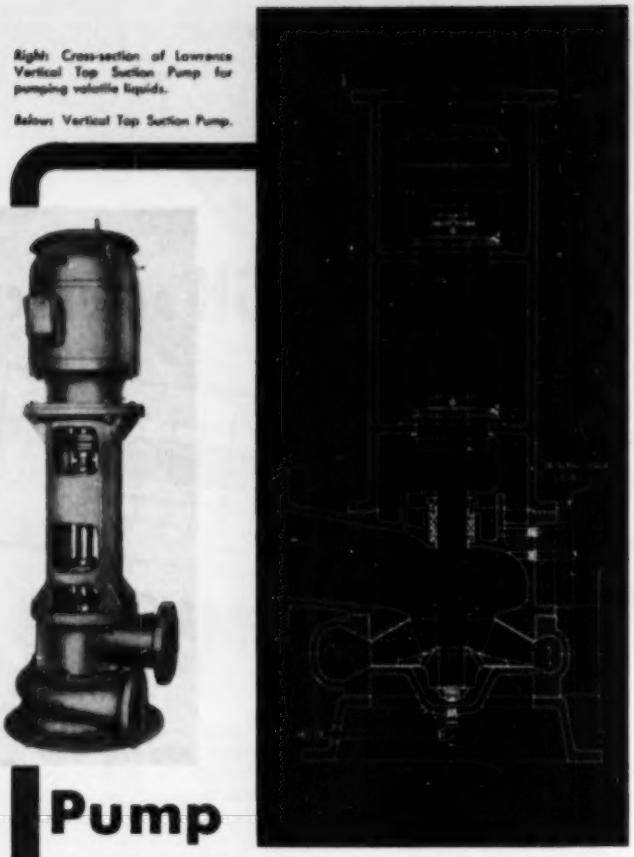
Right: Cross-section of Lawrence Vertical Top Suction Pump for pumping volatile liquids.

Below: Vertical Top Suction Pump.



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When handling volatile liquids under a very low Net Positive Suction Head—from evaporators, for example — a horizontal pump is apt to become vapor-bound. Air or vapor binding is impossible if you install the Lawrence Vertical Top Suction Pump illustrated above. Extremely high vacuums are maintained by filling the space around the packing box with water or some other sealing liquid. The costly delays and shutdowns resulting from vapor binding and loss of vacuum are completely eliminated.

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NEW ENGLAND

(*Continued from page 16*)

bone of New England industry. By nearly every index business is in a healthy shape in New England. Plans are afoot to put up a complete steel mill in New England. This appears to be an attractive prospect: New England steel consumption can well support a mill. Labrador ore with coke by sea from Hampton Roads and limestone from Maine answer the raw material question.

Chemical Industries. What is the state of the chemical industry in New England? Here's how Bradley Dewey, president of Dewey and Almy Chemical Co., brings the situation into focus: "The chemical industry in New England does more than serve regional needs. Unblessed by a plentiful supply of raw materials, the New England chemical manufacturer has concentrated his efforts on new products, specialties, that have come from research and ingenuity. . . ." And the Dewey and Almy Co. has done just that. Starting out with a labor force of five men thirty years ago, the company has grown into a large plant employing hundreds, with branches in this country and overseas, producing can-sealing materials, adhesives, fluxes, wetting agents, and rubber goods.

At the start, of course, chemical manufacturing was begun in response to the demands for chemicals needed in the early tanneries and textile mills. These markets consumed large quantities of basic chemicals produced locally, but depended on foreign sources for dyes and specialties. The Merrimac division of the Monsanto Chemical Co., in Everett, Mass., one of the largest producers of heavy chemicals in New England, originated as the A. Cochrane Chemical Works in 1847. Sulfuric acid was the main product, and the present plant still produces it, along with the other heavy acids, alcohol, ammonia, solvents, and lacquers. The first electrochemical plant in the country was built in Rumford, Me., to supply caustic to the paper mills.

Smaller manufacturers soon grew up to supply the demand for specialized products. Many a small chemical plant found a beginning in the opportunity to market a specialty which the larger, more inflexible plants were unable to produce. Some of these have remained mixers of chemicals marketing a single product, others have chosen to grow, applying New England ingenuity through research, to become diversified manufacturers of important products.

Small or large, these New England

NEW ENGLAND

chemical manufacturers taken together produce chemicals and chemically processed materials in almost every category: oil refinery products, soap, solvents, paint, compressed gases, dyes, acids, rubber, fertilizer, leather, sugar, ink, adhesives, paper, plastics; the list amounts to a business of considerably more than half a billion annually. And yet chemical industry does not stand out as a feature of the region as oil does for Texas or steel for Pittsburgh because the chemical industry is a part of the bustling, diverse Yankee business establishment that presents so many facets that none overshadows another.

Equipment design for all types of chemical industry has profited from Yankee inventiveness. In Boston alone the design and construction activities of E. B. Badger and Sons Co., Stone and Webster Engineering Co., and Artisan Metal Products have been utilized by chemical concerns throughout the world.

John J. Healy, Jr., of Monsanto's Merrimac division and chairman of the Boston Regional Meeting, sums it up in part thus:

> Although New England does not have any single huge chemical engineering development, based on a natural raw material, it has within its borders a large number of chemical manufacturing operations representing almost every phase of chemical engineering development.
>
> New England offers chemical manufacturers three advantages: it is close to one of the most active research centers in the country; it is close to a major market for the consumption of chemicals; it has ready access to deep water and can, therefore, import many raw materials cheaply. . . ."

Ingenuity and Research. This business of Yankee ingenuity that has received so much credit for New England's favorable industrial position deserves examination. Is it an inborn trait reserved for those with a down-East drawl? Perhaps so, but it will be nearer the truth to point out that New England has discovered that original and continuing research applied in liberal quantities pays off in keeping ahead of the crowd.

Research is a vital part of the New England industrial story. Earl P. Stevenson, president of Arthur D. Little, Inc., states the case in part:

> It is peculiarly appropriate that industrial research should have found a center in the New England area, for it had its earliest beginnings there. When Samuel Luther Dana utilized scientific method to evolve a new dyeing process at the Merrimack Manufacturing Co. in Lowell, Mass., in 1834, neither he nor his sponsoring company dreamed that he was the forerunner of a

(*Continued on page 38*)

LAH* reduces carbon dioxide at room temperature and pressure!

Hydrides — industry's great new tools for synthesis and reduction — are making laboratory curiosities possible . . . **and practical!** For example, by using ethereal LAH (Lithium Aluminum Hydride) as a reagent, carbon dioxide is readily reduced to methylalcohol **at room temperature and pressure:**

$$C(=O)=O + LiAlH_4 \rightarrow (CH_3O)_4LiAl \xrightarrow[H_2O]{HCl} CH_3OH + LiCl + AlCl_3$$

Ref: Nystrom, Yanko, Brown, J. Am. Soc., 70, 486-489 (1948)

Reductions of this type ordinarily do not act on olefinic double bonds and require only equipment normally available. Several users are now performing reductions on a commercial scale with LAH* available from Metal Hydrides Inc.

* (Lithium Aluminum Hydride)

Metal Hydrides Inc. is a pioneer in the production of Hydrides on a commercial scale. These highly reactive, diversified compounds, are now available in powdered or lump form as Hydrides of Titanium, Zirconium, Tantalum, Sodium, Barium and Calcium.

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WE ARE PROUD AND CONFIDENT OF EVERY FABRICATION . . .

WHICH MEANS MONEY SAVED FOR YOU!

The tank shown above was one of two on the order 102" I.D. × 28' 1¼" high overall. They were fabricated by DOWNINGTOWN in accordance with the ASME Code, Par. U-68 for 400# working pressure. The shells are 1-9/16" thick of SA-212 Firebox, Grade "B" Steel, and the heads are ASME Code, Elliptical, 1½" minimum thickness of SA-212 Firebox, Grade "B" Steel. The two tanks were hydrostatically tested at 600#, hammer tested, then subjected to an 800# hydrostatic test. Tanks were stress relieved after fabrication by heating from 1100° to 1200° F., and held at that temperature for at least one hour per inch of thickness . . . and, finally, sandblasted inside and outside previous to painting.

The Engineers and Technicians at DOWNINGTOWN have given considerable study to many factors and processes of Plate Fabrication. Consequently, we have arrived at conclusions which we firmly believe assure a quality job. It is true that our procedures sometimes result in a higher initial cost, but for service, the additional expense involved should prove to be good insurance.

Your inquiries for pressure vessels of Nickel Clad, Stainless, Stainless Clad, Carbon Steel, are solicited. Another important factor of our business is the design and fabrication of Heat Exchanger Equipment.

NEW YORK OFFICE: 30 CHURCH STREET

DOWNINGTOWN IRON WORKS
DOWNINGTOWN, PA.
WELDED and RIVETED PRODUCTS

NEW ENGLAND

(Continued from page 37)

profession which 112 years later would have 133,000 workers, employed in 2400 industrial research laboratories all over the United States, nor that $450,000,000 might be spent in one year alone to keep them busy.

The area has had a long tradition of industrial growth in spite of a grave lack of natural resources. Yet whether it is a question of sending clipper ships to China seas, or changing the face of a modern industry, New England seems to have one natural resource to compensate for her stony soil, lack of valuable ores, and minute land area. Ingenuity and initiative, versatile craftsmanship, engineering skills, ability to calculate risk and willingness to take risk, patience, and the nose for markets, are elements native to the New Englander. . . ."

A possible future addition to New England research installations is a proposed Quartermaster Corps laboratory with Cambridge as the natural choice for the site. Another indication of expansion is Esselen Research Corp., which has recently become Esselen research division of United States Testing Co.

So attractive are the potentialities of research that the American Research and Development Corp. has recently been founded in Boston to provide capital for the exploitation of promising new developments. It has already fostered such organizations as Ultrasonics, Inc., pioneers in its field; Ionics, Inc., now working in the important new field of ion exchange, and others.

Educational Leadership. The educational opportunities offered by the schools and colleges of the region have played an important part in moulding the character of New England. Looking back, it appears that the colonists thought about schooling with the second breath they drew in the new land. Harvard University was founded in 1636, being the first college in America. As the nation grew, other colleges were established: Yale, 1702; Dartmouth, 1754; Brown, 1764; Williams, 1785. In the nineteenth century more were added to the list; Bowdoin, Amherst, Tufts, Massachusetts Institute of Technology, Boston University, Worcester Polytechnic Institute, and Clark. A relative newcomer to the educational field is Northeastern University. The women's colleges, Mount Holyoke, Smith, Wheaton, should be added to the count of more than 100 institutions of higher learning New England supports.

Walter G. Whitman, head of the department of chemical engineering at MIT, expresses his enthusiasm. "New England can be justly proud of her schools and colleges. Not only have

NEW ENGLAND

New Englanders pioneered in educational methods; her educational system is notable throughout the world . . ."

Research in the sciences is an important part of the contribution of the colleges to New England life. While the industries must concentrate on the more practical problems of the day, the school laboratories are considering the basic researches that bring dividends in the future.

Fun for All. One natural resource in plentiful supply in New England is snow. And snow has been turned into a cash crop. Within the last twenty years winter sports have made a year-round proposition of the recreational industry that finds a perfect setting in the mountains, lakes, and seashore of New England. Skiing is a million-dollar business, and more important, exhilarating sport.

Summer finds millions of tourists and vacationers coming to New England to enjoy the beaches, to climb on the trails of the White Mountains, to fish in the fast, clear streams, to relax at one of the famous summer hotels. These visitors are joined by New Englanders who make good use of the vacationland at their doorstep. A college student can join his Outing Club for a week-end climb on Mt. Chocorua, a mill worker can fish his favorite trout stream after work, or the family can take Sunday at the beach without going far.

The New Ocean House in Swampscott on Massachusetts North Shore, is well placed for those attending the meeting to become acquainted with all the varied New England scenes. Swampscott itself has many roots in colonial history. The Humphrey House, built in 1634, and the oldest house in Massachusetts is in Swampscott and within a short drive from the hotel are Salem, Gloucester, Lexington, and Concord. Boston, twelve miles away, remains the Hub of New England, if not the universe.

Members of the Institute will have an opportunity to enjoy famous New England sea food, especially featured as a capper for the technical sessions. With the meeting dates not far off from summer, the shore weather should be at its best. The temperature of the ocean waters in May remains somewhat on the cool side, but hardy souls will be welcome to exhibit their natatorial talents between the sessions on fluidization and ultrasonics. The hotel is one of the foremost resort spots in America and boasts a fine beach. A private golf course adjoins the hotel and will be available to members.

(The End)

Filter Facts

IN THE INTEREST OF BETTER PROCESSING

That's An Idea!

In England plate and frame filter presses are finding favor over vacuum filters for filtering sewage sludge. The reason is dry, easily handled and disposable filter cake obtained, with 40% moisture or less, compared with 70 to 80% moisture in cake from vacuum filters.

Preliminary treatment of the sludge with steam results in a fast settling slurry with altered gel structure and reduced affinity for water on the part of the solids. Most of the water is decanted from the settled material, leaving a thick slurry for filter pressing.

●

In filtering hot slurries it is not always necessary to use a jacketed filter press. Desired filtration temperature for effective flow rates can be maintained in vented three-eyed, as well as double-feed, double-discharge four-eyed filter presses. The vent outlet or one of the feed channels is used to circulate hot solution between the filter and the heated supply tank, thus keeping the press and the solution at the desired temperature.

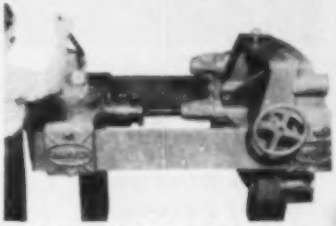
●

A novel investigation was recently completed in the Shriver Lab to control polymerization of a synthetic resin. This plastic requires a heat input to start the reaction, but once under way, the exothermic reaction must be carefully controlled to avoid formation of bubbles.

Using a jacketed filter press, similar in design to a Shriver Wax Cooler, the monomer was charged into the frames exposed to the heating or cooling action of the jacketed plates. At the start of the process, hot water was used to raise the temperature of the monomer to the reaction point. Here the hot water was cut off and circulation of cold water started.

The large area of the mix exposed to the cooling surfaces of the plates provided a rapid transfer of the heat generated by the exothermic phase of the reaction. The result was the production of clear, bubble-free plastic in the form of square cakes, 1" thick.

Say Good-by to the Tommy Bar



By installing a Shriver Hydro-Kloser on any Shriver 24", 30" or 36" filter press, manual closing is eliminated and faster, safer, tighter closure is assured. Hundreds of these units in use prove their value through savings in closing time and reduction in lost-time accidents, and in improved labor relations.

The Hydro-Kloser assembly is easily installed at moderate cost. A few strokes on the hydraulic pump mounted on the screw standard closes the press at proper pressure. Opening the press takes but a few seconds.

Bulletin 128 tells the whole story. Ask for a copy.

Variations on an Old Theme

Here's one — this tilting type filter press permits filtration with filtering surfaces in a horizontal position, and cleaning with plates and frames in a vertical position. It offers the advantages of horizontal plate filtration where filter aids and cake constituents may form a uniform cake over the filter surface, which is not disturbed by starting or stopping the feed at will.

A worm and worm wheel tilt the press by turning the crank handle. This operating principle can be applied to any size filter press.

T. SHRIVER & COMPANY, Inc., 812 Hamilton St., Harrison, N. J.

Quality Tower Packing

in stoneware or porcelain

Pictured above are two popular types of Knight-Ware Tower Packing; Berl Saddles and Raschig Rings. Made in Knight-Ware acid-proof stoneware and porcelain, these shapes and sizes provide a quality tower packing for nearly every chemical use.

All Knight-Ware Tower Packing is made from selected, washed and de-aired clays. Each type will withstand severe acid service, has a high crushing strength and will not spall. The one-inch Raschig Rings, for example, have shown an average of 125 lbs. in break tests. Both Knight chemical stoneware and porcelain packings are dense but not glassy. When desired, porous packings can be made of either material.

Because of their large effective surface area, low resistance to flow and high loading capacity, the most popular all-purpose tower packing is Knight-Ware Berl Saddles. These are available in ¼", ½", ¾", 1" and 1½" sizes. Raschig Rings are available in ¼", ⅜", ½", ⅝", ¾", 1", 1¼", 1½", 2" and 3" sizes.

MAURICE A. KNIGHT

703 Kelly Ave., Akron 6, Ohio

KNIGHT-WARE CHEMICAL EQUIPMENT

PERSONALIA

F. C. FRARY

McCLURE HONORED BY COM. CHEM. DEV. ASSOC.

Harry B. McClure will be the recipient of the first Commercial Chemical Development Association Honor Award. An announcement to this effect was made recently by C. D. Goodale, president of the Commercial Chemical Development Association and Chairman of this year's award committee. Mr. McClure will receive the award scroll at a banquet highlighting the annual meeting of the Association at the Roosevelt Hotel in New York, N. Y., March 22. The subject of Mr. McClure's address on this occasion will be "Recent Case Studies in Chemical Development."

The CCDA Honor Award, being given for the first time this year, has been established by the association to provide annual recognition of an individual who has made outstanding contributions to the commercial chemical development field. Mr. McClure, now division vice-president of the Carbide and Carbon Chemicals division, Union Carbide and Carbon Corp., has devoted his energies to this field since 1931.

Mr. McClure joined the Carbide organization in 1928 after receiving the B.S. and M.S. degrees from the University of Pennsylvania. The honorary degree of D.Sc. was conferred upon him in 1948 by Morris Harvey College, Charleston, W. Va.

H. F. Willkie, vice-president in charge of production, Joseph E. Seagram & Sons, Inc., was recently elected to the board of directors of the International Dairy Exposition. He will serve through December, 1951.

FRARY, FORMER A.I.Ch.E. PRESIDENT, HONORED

Francis Cowles Frary, President of A.I.Ch.E. in 1941, and director of research of the Aluminum Company of America, received the 1950 James Douglas Medal at the annual meeting of the American Institute of Mining and Metallurgical Engineers held at the Statler Hotel, New York, N. Y., Feb. 15, 1950. Dr. Frary was honored "for distinguished achievement in science and contribution to society by broadening the field of knowledge in all phases of the aluminum industry, and for his notable success in directing a vast research project in this industry."

Dr. Frary received a Ph.D. degree from the University of Minnesota in 1912. He was an instructor and assistant professor of chemistry at that university (1905-15); research chemist, Oldbury Electrochemical Co. (1915-17) and Captain Ordnance Department, O.R.C., Major C.W.S. (1918). A year later he became associated with the Aluminum Company of America.

Dr. Frary co-authored "The Aluminum Industry," a McGraw-Hill publication, and holds numerous patents.

Born in Minneapolis in 1884, Dr. Frary has been active in A.I.Ch.E. affairs. Besides holding the highest office, that of President, he served as director for many years and was a member of the Committee on Ethics.

Herbert Pursell, Jr., has been transferred from the Marietta plant of the American Cyanamid Co. to the Bound Brook (N.J.) plant of the Calco chemical division.

H. B. McCLURE

Bachrach

E. R. KENT

Eric R. Kent of the research and development department, Socony-Vacuum Laboratories, Paulsboro, N. J., has been selected to receive the 1950 incentive fellowship award of the Socony-Vacuum Oil Co., Inc., for advanced study for a Doctor's degree.

Mr. Kent, now a U. S. citizen, was born in Vienna, Austria. He obtained the degree of M.S. in chemical engineering at the University of Michigan in August, 1947. After a year's study he joined the Socony-Vacuum Laboratories in October, 1947 where he was assigned to the process development division. He is the author of several patents which are pending on methods of wax purification.

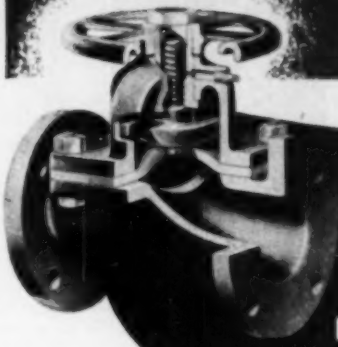
L. G. Alexander, formerly research assistant professor, University of Illinois, Urbana, Ill., is now affiliated with the school of chemical engineering, University of Oklahoma, Norman, Okla.

S. V. JENKINS

Schuyler V. Jenkins is the new representative in the chemical field for Sprout, Waldron & Co., Inc., manufacturing engineers of Muncy, Pa. His territory will cover New York State. Mr. Jenkins was associated at one time with Carbide & Carbon Chemicals Corp., and for a longer period with the Du Pont Company, where among his assignments was the supervision of design of equipment and plants for chlorinated hydrocarbons and solvents, sodium, etc. His specialities in chemical engineering include fluid flow, heat transfer, evaporation filtration, and electrolysis.

(*Continued on page 42*)

Now you can valve ~~66° Baume Sulphuric Acid~~ **without leakage, dripping or sticking**



HILLS-McCANNA *Diaphragm Valves* **with L-1 PLASTIC DIAPHRAGMS**

NEWLY developed plastic diaphragms for Hills-McCanna Diaphragm Valves now make it possible to handle 66° Bé sulphuric acid without leaking, dripping or sticking. The combination of the proved Saunders Patent pinch clamp principle with the new plastic diaphragm puts an end to these troubles so common in valving 66° Bé sulphuric.

Hills-McCanna Diaphragm Valves for handling 66° Bé sulphuric are suitable for temperatures up to 125° F., pressures up to 100 psi. To get complete information, price and delivery data, write today. Specify valve sizes (½" to 4" incl.) and body material (cast iron, cast steel, Durimet or glass lined) desired. Full explanation of the Saunders Patent principle and specifications for Hills-McCanna valves for other services are given in Catalog V-48, available on request. HILLS-McCANNA COMPANY, 2438 W. Nelson Street, Chicago 18, Illinois.

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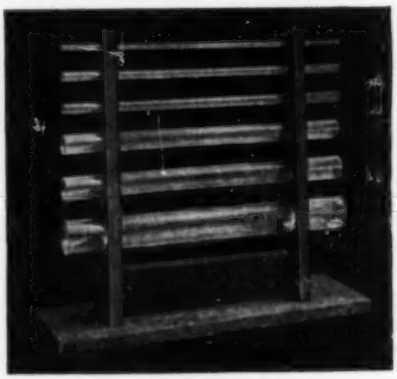

Send for Bulletin #9 covering specifications and prices on standard sizes

VITREOUS SILICA — VITREOSIL

The THERMAL SYNDICATE Ltd.

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PERSONALIA

(*Continued from page 41*)

H. R. ERWIN

Howard R. Erwin, former technical superintendent of the Goodyear Synthetic Corp.'s plant at Torrance, Calif., has been named special representative of the chemical division of The Goodyear Tire & Rubber Co. Mr. Erwin has been assigned to the Cleveland district. He is a graduate of Iowa State College, and is affiliated with Buffalo, Akron and Los Angeles rubber groups.

J. H. Cope, formerly instrument engineer, Hydrocarbon Research, Inc., is now associated with the Fisher Governor Co., Marshalltown, Iowa. His title is assistant sales manager.

S. M. Hulak has recently been transferred from the Niagara Falls (N.Y.) plant of B. F. Goodrich Co., to its Louisville plant.

E. F. WAGNER

Dr. Edward F. Wagner has been appointed head of the recently reorganized technical service department of the Witco Chemical Co., 6200 West 51st Street, Chicago, Ill. Dr. Wagner received his training in chemical engineering at Illinois Tech and spent a number of years in the petroleum industry. He has been with Witco for the past five years in various executive capacities.

Six departments have been set up in the technical service laboratory to handle problems on the various products manufactured by the company.

THORP, CHMN. CHEM. ENG. RESEARCH, ARMOUR

Clark E. Thorp has been named chairman of chemistry and chemical engineering research at Armour Research Foundation of Illinois Institute of Technology. An announcement to this effect

C. E. THORP

was made recently by William E. Mahin, director of research at the foundation. Mr. Thorp will head a department of 95 scientists and technicians now engaged in research projects for industrial concerns and government agencies. He has been associated with the foundation since 1941.

As assistant chairman of the department, Mr. Thorp has been in charge of all chemical engineering activities for nine years.

Mr. Thorp was director of research for the Ozo-Ray Process Corp. from 1937-41. He was chief chemist for Fullers Earth Co. from 1936-37 and analytical chemistry for National Lead Co. in 1935 and 1936.

He received his B.S. degree from Penn College in 1935, and in 1937 received a degree of M.S. from Western Reserve University. He is the author of numerous scientific papers on ozone.

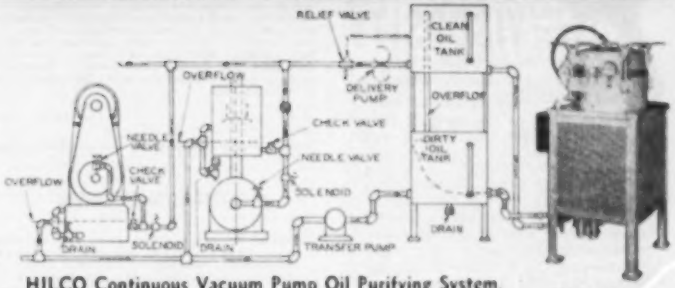
R. M. HUNTER HONORED BY CASE

Ralph M. Hunter, manager of the electrochemical division, The Dow Chemical Co. and a director of Dow Chemical of Canada, Ltd., received the honorary degree of Doctor of Engineering by the Case Institute of Technology Jan. 28, 1950, "in recognition of industrial achievements and of technical services to the United States Government and of contribution to Case through leadership in alumni activities."

Dr. Hunter received the degree of B.S. in chemical engineering from Case in 1918 and the professional degree of chemical engineer in 1931. He began his career with The Dow Chemical Co. in Midland, Mich., as an employee in the chlorine department.

(Continued on page 45)

BETTER *Vacuum* WITH *The* HILCO OIL RECLAIMER



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free from abrasive solids, varnish forming substances and especially volatile contaminants which raise vapor pressure and decrease processing efficiency.

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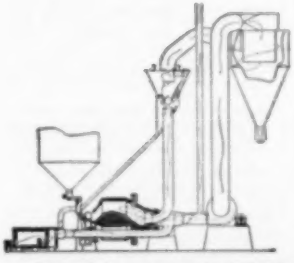

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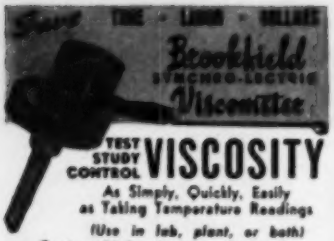

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INDUSTRIAL TOXICOLOGY

By HERVEY B. ELKINS

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March, 1950
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Advertisements in the Classified Section of Chemical Engineering Progress are payable in advance, and are placed at 15c a word, with a minimum of four lines accepted. Box number counts as two words. Advertisements average about six words a line. Members of the American Institute of Chemical Engineers in good standing are allowed one six-line insertion free of charge per year. More than one insertion to members will be made at half rates. In using the Classified Section of Chemical Engineering Progress it is agreed by prospective employers and employees that all communications will be acknowledged, and the service is made available on that condition. Boxed advertisements one-inch deep are available at $15 an insertion. Size of type may be specified by advertiser. In answering advertisements all box numbers should be addressed care of Chemical Engineering Progress, Classified Section, 120 East 41st Street, New York 17, N. Y. Telephone OREgon 9-1560. Advertisements for this section should be in the editorial offices the 25th of the month preceding the issue in which it is to appear.

SITUATIONS OPEN

Chemical Engineer—Pilot plant and development work. Eastern location. 5-8 years' experience, preferably man with great initiative, resourcefulness and qualities of leadership. At least M.S. degree desired. Give details education, personal data and salary requirement. Box 1-3.

Chemical Engineer Supervisor — Attractive opening eastern location for pilot plant supervisor with broad experience organic chemicals. Please submit complete resume and salary desired. Box 2-3.

Chemist or Chemical Engineer—To work under guidance of experienced chemist on textile dyeing and related problems, but must be capable of carrying on independent program. Initiative and diplomacy are desired. Location midwest. Give details, education and experience. Box 4-3.

SITUATIONS WANTED

A.I.Ch.E. Members

Chemical Engineer—Ph.D., age 34. Thirteen years of diversified and responsible industrial experience covering catalytic cracking, complete refinery design and revamp, atomic energy design, light-ends recovery and oxygenated compounds separation. Strong in distillation, absorption, extraction and adsorption. Experience ranges from process design and development to project engineering. Desire responsible position requiring technical, administrative and organizational ability. Box 3-3.

University Teaching and Research—Position in chemical engineering. Purdue, B.S.Ch.E., 1942; Michigan, M.S., 1943; Ph.D., June, 1950. Two years' industrial experience, four years teaching. Fellowships, societies. Age 29; married. Box 5-3.

Production Engineer—Chemist—B.S. 1933. Sixteen years' experience with major companies in plant operation, starting new plants, product development, control, instrumentation, safety and cost. Twelve years organic synthesis. Experienced in batch and continuous processes. Box 6-3.

Chemical Project Engineer—B.S.Ch.E., 1940. Process design, equipment design, cost estimates, plant layout, purchasing, specifications, contracts, erection, plant start-up, production. Organic chemicals and pharmaceuticals. Many unit operations, unit processes. Eastern location. Box 7-3.

Chemical Engineer—B.S. 1942. Two years graduate work. Five years' experience petrochemicals, petroleum, and chemical processes. Process design, development, economic analysis, supervision. Excellent scholastic record; references. Interested in any phase engineering offering real opportunity. Box 8-3.

Chemical Engineer—B.S., age 28, married, family. Seven years' experience in design, process development, and pilot plant operation. Group leader for past three years. Desire responsible position consistent with experience and offering improved opportunity. Box 9-3.

Sales Engineering—B.S.Ch.E., Univ. of Illinois, 1948. Two years' experience in petroleum engineering. Change desired. Age 26; three years military, commissioned. Job location secondary. Currently residing in North Jersey. Available immediately. Box 10-3.

Chemical Engineer—B.S. Chem., 1942, B.Ch.E., 1949, age 30, married. Eight years' experience in analytical labs.; foreman in explosives mfg., rubber development including compounding, design of new products, technical sales service. Box 11-3.

Teacher of Chemical Engineering—Ph.D., June, 1950. Age 31, single. Five years' industrial experience, four years' teaching experience. Desire permanent teaching position with time for research. Box 12-3.

Creative Chemical Engineer—Ph.D., Spring, 1950. Eight years' experience as pilot plant supervisor and research group leader for catalytic synthesis of petroleum and organic chemicals. Interested in a position that requires leadership and originality based on a strong theoretical and practical background in chemical engineering. Box 13-3.

Chemical Engineer—31, M.I.T., 1940, 9½ years' experience process design, plant operation and project engineering with internationally known contracting firm and large oil company, specializing in oil, light hydrocarbons, and petrochemicals. Desire engineering group leadership or similar responsible position with organization planning expansion. Box 14-3.

Administrative Assistant — B.Ch.E., Yale, 1942, married, family. Presently studying business administration. Diversified engineering experience; USNR officer; process, product development. Desire opportunity to advance into technical, plant management. Employed. Box 15-3.

Chemical Engineer — B.S., 1934, married, family, 39. Sixteen years' experience in design, engineering, construction and operation of chemical plants. Desire responsibilities in administrative capacity. Box 16-3.

Chemical Engineer—B.Ch.E., 1942. Eight years' experience process development, design and operation. Major experience project engineering in organic chemical field, including operational investigations. Primarily interested in qualifying for responsible position medium-sized industry in East. Box 17-3.

Chemical Engineer—M.Ch.E. Require responsibility, job must challenge initiative. Plant design, pilot plant, control. Third year of refinery design following customers requirements through design, equipment selection, erection drawings. Graduate thesis on food yeast fermentation. Box 18-3.

Chemical Production Man—Ten years of operation, development, layout organic pilot plant, fats and oils refining, high vacuum distillation. Complete competence in handling people and processes. Top references. Box 19-3.

Supervisory Chemical Engineer—B.S., 31. Experienced in supervision, operations, pilot plant development, plant design, and economic studies of petroleum and petrochemical plants. Desire responsible engineering position with small company. Box 20-3.

(Continued on page 45)

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SIMPLE TO ADJUST FOR THE SPECIFIED OPERATING RANGE

MERCOID CONTROLS ARE EQUIPPED WITH MERCURY SWITCHES, THEREBY INSURING GREATER SAFETY, BETTER PERFORMANCE AND LONGER CONTROL LIFE

WRITE FOR CATALOG 600-B.

THE MERCOID CORPORATION
4201 BELMONT AVE. CHICAGO 41, ILL.

CLASSIFIED SECTION

(Continued from page 44)

Situations Wanted

Chemical Engineer—32. Five years in research, development, and process engineering, and 3½ years in project (chemical) engineering. Experienced chemicals, petrochemicals, organics from process development and pilot planting, economic appraisal and process design, through engineering, construction, operation, and process improvement on either small or large scale. Administrative ability. B.S., M.S. credits. Box 21-3.

Sales Engineer—B.Ch.E. 1947, married, veteran, 27. 2½ years' diversified development and production experience, translate chemical data and sales correspondence in German or Spanish. Interested in selling chemical products or processing equipment. Box 22-3.

Executive Engineer—Chemical engineer engaged in direction of group designing plants for soaps, detergents, chemicals, and pharmaceuticals. Seek position as chief engineer. In present position have overall responsibility for projects. Metropolitan area preferred. Box 24-3.

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Chemical Engineer—B.Ch.E. Recent graduate, high scholastic standing. Desire position with future. Will relocate. Army Chemical Corps and Technical Intelligence experience. Box 23-3.

Space Available—700 sq. ft. suitable for an office for consultant or organization identified with chemical profession or industry. Will make extensive alterations for desirable tenant. Apply: Manager, Chemists Building, 50 East 41st Street, New York 17, N. Y. Le 2-7649.

PERSONALIA

(Continued from page 43)

SHARPLES PERSONNEL IN NEW CAPACITIES

Sharples Chemicals Inc. announces the following personnel changes in its Wyandotte (Mich.) plant.

Howard F. Bjork, formerly production manager, is now plant manager. Mr. Bjork has been with the company 13 years.

Robert P. Ogden, formerly superintendent of the service department, is now production manager.

J. W. Mayers, formerly assistant to the vice-president-production, has been appointed chief engineer.

Donald W. Beery has been appointed senior engineer in the recently organized synthetic fuels and chemicals department, Blaw-Knox Co., Pittsburgh, Pa. Mr. Beery went to Blaw-Knox in 1948 after 10 years' technical experience in chemical processing. Much of this involved pilot plant operation and process design in such fields as petroleum processing, varnish and plastics production, synthetic rubber, and natural and synthetic fibers. He is an alumnus (chemical engineering) of Newark College of Engineering and received a Master's degree from Stevens Institute of Technology.

(Continued on page 46)

The Liquid Plastic that STOPS CORROSION

PRUFCOAT

PROOF against Acids, Alkalis, Salt, Oil and Water

*Article in C. & E. News Vol. 27 — 939

"Prufcoat proven superior to all other coatings we have tested" . . . writes one of America's largest chemical companies, after eight years' experience with Prufcoat. And this is just one of many reports on file testifying to the effectiveness of Prufcoat's famous liquid plastic formulations in controlling corrosion caused by chemical agents such as these:

Acetic Acid	Muriatic Acid
Alcohols	Nitric Acid
Bleach Solutions	Oleic Acid
Calcium Chloride	Oleum
Chlorine	Phosphoric Acid
Cyanides	Salt Solutions
Formaldehyde	Sugar
Hydrofluoric Acid	Sulfonated Oils
Lactic Acid	Sulphuric Acid
Lubricating Oils	Sodium Hydroxide

Send today for a *Prufcoat PROOF Packet*. Contains in one easy-to-file folio outside laboratory tests, case histories, and Prufcoat Protecto-Graph Plan for analyzing your own painting maintenance costs. *Write Prufcoat Laboratories, Inc., 63 Main St., Cambridge 42, Mass.*

SAVES More because it PROTECTS More

8 Attractive Colors that Apply Like Paint to Masonry, Metal, Wood

YOU GET POSITIVE CORROSION RESISTANCE ON ALL!

Tanks 10 ft. in diameter, 12 ft. deep—or pipe fittings no larger than your thumb. Every piece of process equipment in your plant can be made *positively* corrosion resistant for longer service life, lower maintenance costs. HAVEG, the strong, lightweight molded material, resists chemical action *through its entire mass.* Not just a lining or coating, its performance is not affected by surface gouges or abrasion.

We're sure HAVEG can help you increase equipment life—so sure that we ask you to try it. Send for samples or install a test piece. Meanwhile, for detailed engineering and application data, write for Bulletin F-5, today.

Available in complete range of sizes to meet all process equipment needs!

HAVEG CORPORATION
NEWARK 99, DELAWARE

PERSONALIA

(Continued from page 45)

D. E. JACK

Bachrach

Delbert E. Jack has returned to California to establish his own company as manufacturers' agent. He was formerly vice-president in charge of engineering and sales for The Duriron Co., Inc. He retains his current position on the board of directors of The Duriron Co., and is retained by that company as its West Coast technical director.

John W. Bertetti, formerly chief engineer, Root Petroleum Co., El Dorado, Ark., is now technical director, Pan-Am Southern Corp., El Dorado, Ark. The merger of Pan American Petroleum Corp. of New Orleans, La., with its subsidiary Root Petroleum Co., Shreveport, La., to form Pan-Am Southern Corp. was reported last year in *C.E.P.*

W. D. STALEY

Wayne D. Staley, formerly New York district manager, The Duriron Co., has been appointed general sales manager and will be located at the home office of the company in Dayton, Ohio. In directing sales and advertising activities, he will replace Delbert Jack who has resigned as vice-president in charge of engineering and sales.

R. F. Sharpe, former manager of the Philadelphia office, The Duriron Co., Inc., has been appointed New York district manager.

ZIMMERMAN HEADS CHEM. ENG. AT NEW HAMPSHIRE

Dr. Oswald T. Zimmerman, professor of chemical engineering at the University of New Hampshire, Durham, N. H., who has been teaching the subject in the department of chemistry, will head the newly created department of chemical engineering. Professor Zimmerman is an authority on synthetic resins and hydraulic cements. He was graduated from the University of Michigan in 1929, and received his Master's degree in chemical enginering from Michigan in 1931, and a Ph.D. in 1934. He has taught at the University of North Dakota and has been a research chemist for a Detroit dental manufacturing company. He has been at the University of New Hampshire since 1938.

Necrology

M. J. BAHNSEN

Dr. Monroe John Bahnsen, director of chemical research, Ferro Enamel Corp., died Feb. 4. Born at Port Clinton, Ohio, he attended public school in Port Clinton, and Case Institute of Technology where he received his B.S. degree in chemical engineering in 1929.

He was employed at the Cleveland plant of the Grasselli Chemical Co. until 1930 when he entered the graduate school of Western Reserve University, Cleveland, Ohio. In 1931 he was awarded the Cushman Fellowship for fundamental research in the field of porcelain enamel. He received a Ph.D. in chemistry from Western Reserve in 1934 and had been associated with Ferro Enamel Corp. since that time. He was appointed director of chemical research in 1943 and remained in that capacity until his death.

The Monroe J. Bahnsen Memorial Fund has been established by contributions of friends and associates. This fund is to be used as an annual $100 award to the senior student in the department of chemistry and chemical engineering at Case Institute of Technology, Cleveland, Ohio, who is selected for the most outstanding work in the course in chemical engineering projects.

F. E. DODGE

Frank Ellsworth Dodge, retired chemical engineer, died Feb. 17 at the Park Villa Nursing Home in Rockville Centre, Long Island. His age was 83. At retirement in 1946 he was with the Midwest Radiant Corp. as chemical engineer. He had previously served in a similar capacity with the National Lead Co.

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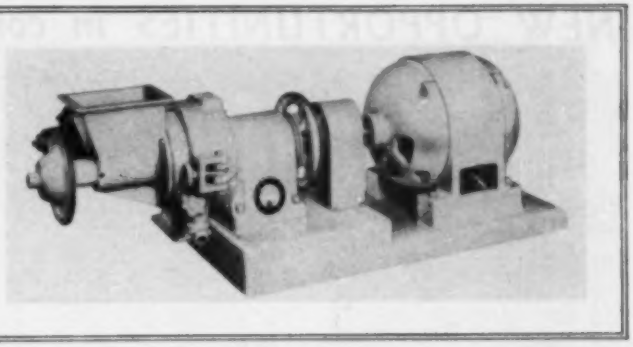

BAUER 8-IN. ATTRITION MILL

GRINDS, MIXES, BLENDS

Any combination of materials capable of being pulverized can be ground, mixed, and blended in this Bauer Single-Disc Attrition Mill. The ingredients are thoroughly dispersed, resulting in complete homogeneity.

The mill illustrated is equipped with a screw feeder which assists the blending process. Accurate adjustment of the discs for coarse or fine grinding is made by means of a large hand wheel with graduated dial. Many patterns of discs are available to meet specific requirements.

Complete information on this and other Bauer Attrition Mills will be gladly furnished. Give us an idea of the kinds and quantities of materials to be processed so that we can make definite recommendations.

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WHAT WILL SUMMER HOT WEATHER DO TO YOUR PROCESS

Croll-Reynolds CHILL-VACTORS frequently show a good profit over the total cost in extra production the first season, and they have many years of maintenance-free service. There are usually extra benefits in better quality and more uniform quality.

CHILL-VACTORS have many advantages, but are not perfect. In general, they are limited to temperatures above 32° F. They require more condenser water than mechanical refrigeration, but almost any natural water, including sea water, can be used. There are too many advantages to list here. The most important are:

Low cost • Can be operated by low pressure steam
No refrigerant except water • No moving parts, noise or vibration
Practically no operating supervision
Some liquids or solids can be cooled direct without brine or other circulating fluid

Made in sizes from a few tons to 1000 tons or more (1 ton = 12,000 B.T.U. per hour)

Individual engineering study will be given without obligation to each industry. This also applies to any industrial vacuum requirement down to a few microns absolute pressure.

CROLL - REYNOLDS CO., INC.

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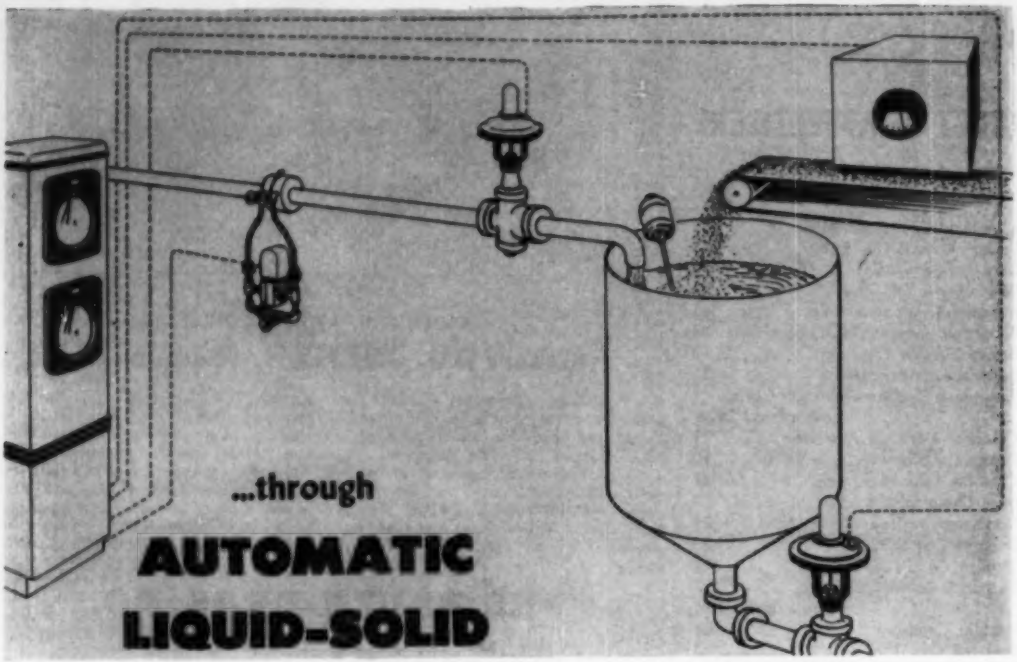
CHILL-VACTORS STEAM JET EVACTORS CONDENSING EQUIPMENT

NEW OPPORTUNITIES in continuous processing



RATIO CONTROL...by Foxboro

Many a troublesome batch process can be converted to continuous operation — with resulting economies and product improvement — by installing Foxboro Liquid-Solid Ratio Control. This simple, accurate system has been thoroughly proved in use on such processes as the extraction, dissolving, or reaction of materials.

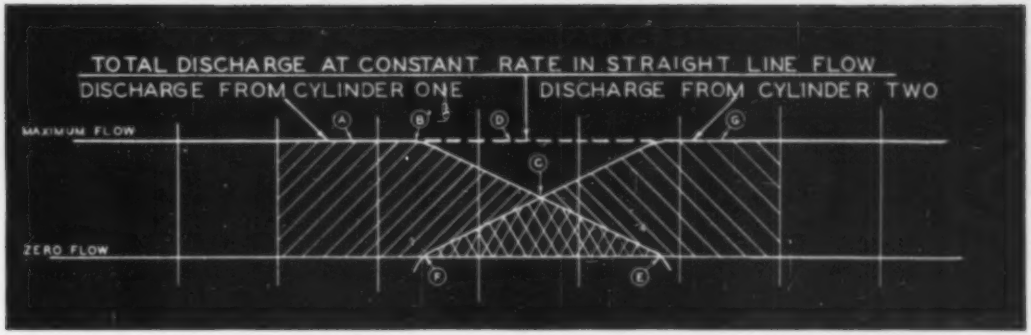
Typical examples include the proportioning of acid feed to phosphate rock in the production of phosphate fertilizer, and the proportioning of water to the feed of crossettes (ground beets) in the production of beet sugar. *Wherever ratio-ing the quantity of liquid reagents to a varying rate of solid chemicals being delivered by a conveyor belt is desirable, this fully automatic system simplifies the operation and improves the efficiency of the process.*

In this system, a Foxboro Recording Controller receives a continuous measurement of weight of the solid material (from a Foxboro Pneumatic Motion Transmitter incorporated in a Merrick Weightometer located above the conveyor belt), and also receives a continuous measurement of liquid flow from a Foxboro d p Cell or mercury manometer. The desired ratio between solid and liquid can be readily set by a dial in the instrument which, in turn, controls the liquid flow.

The efficiency-boosting advantages of Foxboro Ratio Control are now being realized by a number of leading companies. If you have a similar problem, learn how these advantages may be achieved for your plant. Write for engineering data. **The Foxboro Company, 248 Neponset Ave., Foxboro, Mass., U. S. A.**

This illustration shows Foxboro Ratio Control at a large beet sugar plant. A Merrick Weightometer equipped with a Foxboro Pneumatic Motion Transmitter appears in the foreground.

FOXBORO
REG. U. S. PAT. OFF.
COORDINATED CONTROL



"Constametric" pump discharge curves. Showing how two reciprocating plungers deliver at a constant rate of flow.

A—Plunger number one discharges into manifold at maximum flow and constant rate.
B—Plunger one at start of deceleration.
C—Crossover point where discharge by plunger one equals discharge by plunger number two.
D—Combined discharge by plunger one and plunger two. Note the continuation of constant flow.
E—End of discharge stroke and start of suction stroke, plunger one.
F—Plunger two at completion of suction stroke and start of discharge stroke.
G—Plunger two discharging into manifold at maximum flow and constant rate.

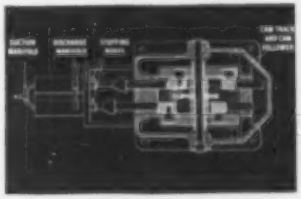
The Controlled Volume Pump that Delivers in Straight Line Flow

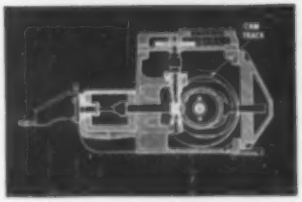
The Milton Roy "Constametric" is a positive displacement, controlled volume chemical pump having a constant flow delivery without pulsation. Two double-ball check liquid ends are employed. The plungers are driven by cams so designed that the speed of one plunger decelerates at the end of its stroke at a rate equivalent to that at which the second plunger accelerates. Since the two liquid ends have common input and output manifolds, the combined delivery of the plungers is at a constant rate of flow at the cross-over point between plunger loadings, as well as during the balance of each plunger stroke. The pumping action is exactly the same as that of a single plunger, moving forward continuously at a fixed rate of speed.

Capacities and Pressures

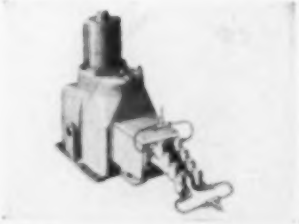
"Constametric" pumps are furnished with plungers from ⅜" to 1¼" dia., to pump from a minimum of 0.07 gallons (250 ml) per hour to a maximum of 57 gallons per hour. Maximum pressures range to 5,000 psi, on the smallest plunger diameter. Automatic, stepless speed regulation over a range of 20 to 1 is obtained by means of the Thymotrol electronic system. Any metered variable, such as flow, temperature, conductivity, pressure, etc., can be utilized to actuate the speed of the pump through this electronic control system, thus regulating the metered rate of discharge.

For typical delivery curves, capacity-pressure table, applications and engineering data, ask for Bulletin 649.





Showing drive mechanism, cam track, cam follower, etc. Milton Roy "Constametric" Pump. Principles of design and application fully covered by patent applications.



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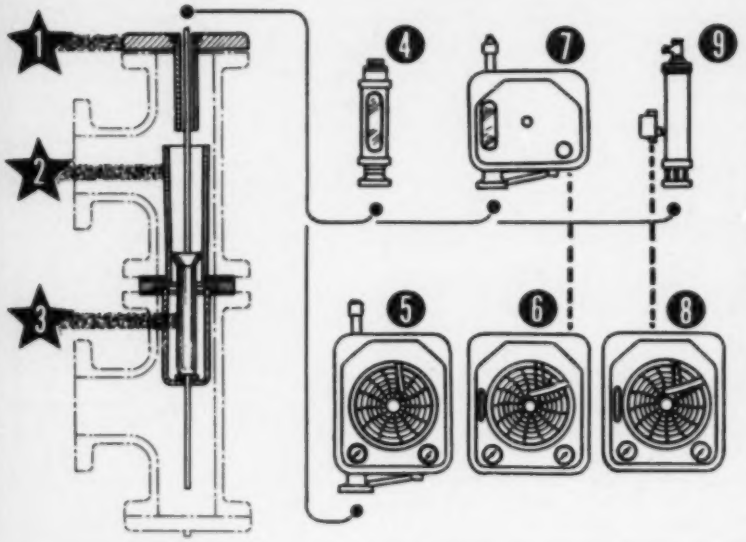
PLANT-WIDE FLOW MEASUREMENT SIMPLIFIED

BY NEW, INEXPENSIVE F & P AREA METER

3 BASIC UNITS IN STANDARD PIPE TEES + **INDICATING, RECORDING OR TELEMETERING INSTRUMENTS** = **COMPLETE FLOW MEASUREMENT**



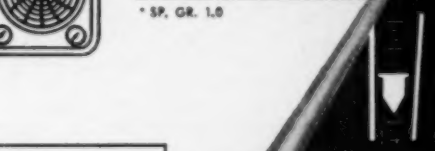
MAXIMUM CAPACITIES (MIN. = 1/10 MAX.)		
PIPE FITTING SIZES	LIQUID* G. P. M.	GASES C. F. M.
2"	16.5	28.0
3"	37.0	55.0
4"	110.0	275.0
6"	336.0	1000.0
8"	750.0	1800.0
10"	1000.0	2500.0
12"	1700.0	4500.0
14"	2700.0	6500.0
16"	3900.0	8500.0
20"	6200.0	12500.

* SP. GR. 1.0

★ BASIC ELEMENTS		
	PART	NO. OF SIZES REQUIRED
★	COVER FLANGE	10
★	SLEEVE	13
★	FLOAT	13

● SECONDARY ELEMENTS					
	PART	NO. OF SIZES REQUIRED		PART	NO. OF SIZES REQUIRED
4	INDICATING	1	7	PNEUMATIC TRANSMITTER	1
5	CLOSE-COUPLED RECORDING	1	8	REMOTE ELECTRICAL	1
6	REMOTE PNEUMATIC	1	9	ELECTRICAL TRANSMITTER	1

Flow capacities from 2 gpm to 6200 are handled with a minimum number of basic metering parts designed for installation *inside* standard pipe fittings. Mountings for Secondary Recorders, Controllers, and Integrators are interchangeable in all sizes.



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$$Q = CA\sqrt{2gh}$$

FLOWRATOR instruments consist of a vertical tapered tube (smallest diameter at the bottom) in which a weighted metering element (float) of fixed diameter is free to move upward or downward. The "float," being of fixed weight, establishes pressure differential "h" as a constant, thus establishing linear relationship between float movement and rate of flow.

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PROCESS CONTROL INSTRUMENTS

FLOWRATOR

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